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Planning Resource Allocations to Research & Development Projects

DOT/FAA/AR-AAR/400

Office of Aviation Research
Washington, D.C. 20591

Date: September 22, 1999

Final Report

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Technical Report Documentation Page

1. Report No. DOT/FAA/AR-AAR/400	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PLANNING RESOURCE ALLOCATIONS TO RESEARCH & DEVELOPMENT PROJECTS (TASKS C/D OF COOP AGREEMENT NO. 98-G-018)		5. Report Date September 22, 1999
		6. Performing Organization Code
7. Author(s) Dr. Les Frair Dr. Robert Batson Amit Desphande DeBarion Taylor		8. Performing Organization Report No. OSEP NO. 656-69
9. Performing Organization Name and Address The University of Alabama		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 98-G-018
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A detailed statement of work of how FAA should allocate resources for research and development projects is presented. First the FAA R&D investment problem is defined. Secondly various candidate solution techniques and methodologies are reviewed for application to the problem of interest. Thirdly a methodological approach for the application of solution methodology to problem is identified.

Combining these detailed investigations with information obtained from the problem definition task, such as division's primary goal(s), sub-goals or objectives and operational requirements led to the conclusion that the Analytic Hierarchy Process (AHP) would be the most effective solution methodology. Evidence is presented that the application of AHP would result in a more effective allocation of operational requirements to technology strategies.

17. Key Words Research & Development Allocations, Multicriteria Decision Making, Analytic Hierarchy Process, AHP		18. Distribution Statement This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

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EXECUTIVE SUMMARY

The objective of this research is to develop a detailed statement of work for a investigation of how FAA should effectively allocate resources for research and development (R&D) projects. This preliminary investigation is concerned with performing the following three tasks. 1.)Definition of an FAA R&D investment problem; 2.) Examination and preliminary evaluation of candidate solution techniques and methodologies; 3.) Development of a general approach for applying solution techniques and methodologies (task 2) to the problem definition (task 1)

To assist in developing a detailed work statement for this problem definition phase UA researchers conducted an extensive literature review of how other large and complex organizations plan for R&D investment. This review included all appropriate publications available to the public. Key word searches using computer-based reference databases will be used to identify the appropriate publications in the private and public sector. Detailed efforts will be initiated to obtain references for review concerning how the respective research offices of NASA, and DOD (Air Force, Army, and Navy) plans for R&D investment. In addition to reviewing published works concerning how other large organizations conduct R&D investment planning personal contacts were made with NASA, DOD and DOT to identify current practices for such planning.

During the problem identification phase (task 1) a number of different solution techniques and methodologies were identified as being used by various parties in the planning for R&D investment. These solution techniques were reviewed and their strengths and weaknesses for application to planning R&D investments enumerated. The potential of the identified solution techniques and methodologies were further assessed based upon their adaptability to producing effective results within the suggested general approach. The results of this step would be a list of leading candidates for detailed further investigation.

Combining these detailed investigations with information obtained from the problem definition task such as the selected division's primary goal(s), sub-goals or objectives and operational requirements as well as the current and planned allocation of these requirements to technology strategies allowed us to recommend that the Analytic Hierarchy Process (AHP) be utilized by FAA will be asserted.

AHP would be used to determine a more effective allocation of operational requirements to technology strategies. It is assumed that the logical future states corresponding to any such possible reallocation would be derived and AHP be employed in an iterative fashion to determine dynamic allocations. Finally it is anticipated that through the use of AHP a backward (chronologically) process can be developed starting with the desired future (most likely between five and ten years from the present) state of the system. AHP is a solution methodology capable of determining what policies, affected parties attitudes and technology options would have to be to make the desired future state most likely. Upon comparing this backward process with the derived logical future(s) a solution methodology capable of determining how we should attempt to control or steer the logical future process to our desired future state can be applied.

A detailed set of recommendations outlines the next steps to be taken to implement AHP for the broad range of FAA resource allocation problems.

1. INTRODUCTION

In today's fast moving technological world, the need for sound, rational decision-making by individual, business, industry, and government is vividly apparent [1]. Making decisions is undoubtedly one of the most fundamental activities of human beings. Humans are faced in their daily lives with varieties of alternative actions available to them, and at least in some instances, they have to decide which of the available actions to take [2]. Multiplicity of criteria and objectives occur in almost every area of decision-making [3]. It is almost impossible for any decision-maker to intuitively take full account of all the factors impinging on a decision simultaneously. It thus becomes useful to find some method or process that would aid the decision-maker in making decisions on complex problems. Decision analysis is concerned with the making of rational, consistent decisions, notably under conditions of uncertainty. It also assists the decision-maker in selecting the best alternative in the light of the information available (which normally is incomplete and has limited reliability) [1]. Decision-making is the science of transforming and relating data about the world to the decision-maker's value system so that he/she can take the necessary actions to fulfill his/her needs, and aspirations. Intellectually, it is the funnel of information and knowledge gathered from experience and from simply noting how things unfold in the environment. Decision-making has become the invariant of all human undertakings [4].

The beginning of decision-making, as a subject of study, can be traced, presumably, to the late 18^{th} century, when various studies were made in France regarding methods of election and social choice [2]. Since these initial studies decision-making has evolved into a respectable and rich field of study. The subject of decision-making is, as the name suggests, the study of how decisions are actually made and how they can be made better or more successfully. Much of the focus in developing the field has been in the area of management, in which the decision-making process is of key importance for functions such as inventory control, investment, personnel actions, new product development, and allocation of resources, as well as many others. Decision-making itself, however, is broadly defined to include any choice or selection of alternatives, and is therefore of paramount importance in many fields in both the "soft" disciplines such as social sciences and the "hard" disciplines such as natural sciences and engineering. The field is concerned, in general, with both the descriptive theories and the normative theories [2].

1.1: VARIOUS DECISION MAKING TECHNIQUES

There are essentially two basic approaches to modeling human decision-making [3]:

1. The "outcome-oriented" approach based on the view that if one can correctly predict the outcome of the decision process, then one obviously understands the decision process. The decision outcome and its correct prediction are at the center of this approach. Normative decision analysis, single- and multi-attribute utility theories etc., are examples of this orientation, which asks questions like what and when rather than how.

2. The "process-oriented" approach based on the view that if one understands the decision process, one can correctly predict the outcome. Essentially descriptive, this approach has prescriptive and normative features as well: knowing how decisions are made can teach how they should be made; the reverse causal linkage unfortunately does not follow.

The current literature on decision-making based largely on theories and methods is enormous. Many different methodologies/processes have been developed and used in a variety of situations. Multiplicity of criteria and objectives has led to the development of "multi-criteria decision-making (MCDM)" and "multi-objective decision-making (MODM)" methods. Participation of more than one individual led to the development of "multi-person or group decision-making" methods. Time and state dynamism led to the development of "multi-stage decision-making" methods. Decision-making methods have been classified in many different ways. Peniwati [5] classifies them as "Structuring methods", "Ordering and Ranking methods", and "Structuring and Measuring methods". Guitouni and Martel [6] classify these methods as "Elementary methods", "Single synthesizing criterion methods", "Outranking methods", and "Mixed methods". Numerous other classifications are available in the literature. Listing and description of all the available decision making methods is considered beyond the scope of this research. However, the popular methods belonging to the broad categories are listed herewith. Appropriate references are provided for each of the method for the interested reader.

Analogies and Attribute Association, Boundary Examination technique, Brainstorming technique, Morphological forced connections technique, and Why-What's stopping are the popular methods that belong to the "Structuring" category of the decision making methods. As the name of the category suggests these are primarily creativity boosting methods that help to look at the problem in different ways, gain fresh perspectives and understand the problem. These methods help formulate and define the problem and provide alternative solutions to the problem. Couger [7] provides an excellent description of these methods.

Voting [5], Nominal group technique (NGT) [5, 7], The Delphi method [5, 7], Disjointed incrementalism technique [5, 7], Matrix evaluations [5, 7], Goal programming (GP) [5, 8], and Conjoint analysis [5] belong to the "Ordering and Ranking" category of decision making methods. "Outranking" methods are also a part of the "Ordering and Ranking" category of decision making methods. The concept of outranking was developed with the motivation to improve efficiency without affecting the outcome while considering less information. The idea is to see whether there are enough arguments to decide that an alternative A_i is at least as good as A_j, while there is not essential reason to refute that statement [5]. Elimination and (Et) Choice Translating Reality (ELECTRE) [6], Preference Ranking Organization Method of Enrichment Evaluation (PROMETHEE) [6, 9], and Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) [6] are some of the methods that belong to the "Outranking" category. A main weakness of the methods is the ordinal way used to combine concordance and discordance that leaves one in doubt about the accuracy of its outcome [5].

DISplaced iDeal (DISD) [10, 11], STEp Method (STEM) [10, 11], and Compromise Programming (CP) [10, 12] belong to the category of "Distance based" methods. Weighted sum [6, 13, 14], Lexicographic method [6, 13], Conjunctive method [6, 13, 14], Disjunctive method [6, 13, 14], and Maximin method [6, 13] belong to the category of "Elementary" methods. Technique for Order by Similarity to Ideal Solution (TOPSIS) [6, 13], Simple Multi-Attribute Rating Technique (SMART) [6], Fuzzy weighted sum [6], and Fuzzy maximin [6] are some of the methods that belong to the category of "Single Synthesizing Criterion" methods. Fuzzy conjunctive/ disjunctive method [6, 15], and Martel and Zaras method [6] are some of the methods that belong to the category of "Mixed" methods.

Bayesian analysis [5, 8], Multi-attribute Utility (Value) Theory (MAUT/ MAVT) [5, 8, 16], Analytic hierarchy process (AHP) [5, 17, 18, 19], and Analytic network process (ANP) [5, 17, 20] belong to the category of "Structuring and Measuring" methods. AHP is the method that has received considerable attention among researchers and practitioners during the last couple of decades. The AHP helps decision-makers structure the important components of a problem into a hierarchical structure similar to a family tree. Then, by reducing complex decisions to a series of simple comparisons and rankings, then synthesizing the results, the AHP helps the decision-maker arrive at the decision [17]. The ANP is a generalization and extension of the AHP that allows feedback and dependence among the decision elements and cluster of elements [5, 20]. The fact that numerous applications of ANP exist show that the AHP can be generalized, and is thus a validation of the AHP itself, as generalizability is a necessary condition for a good decision theory [5]. The MAUT/ MAVT is the method that was considered the panacea to decision-making problems prior to the acceptance of AHP. Multi-attribute Utility (Value) Theory (MAUT/MAVT) attempts to maximize a decision-maker's utility (under uncertainty) or value (preference) which is represented by a function that maps an object measured on an absolute scale into the decision-maker's utility or value relations [5]. The function is constructed by, for example in the case of MAUT, asking lottery questions involving probability to articulate the decision-maker's value tradeoffs among the conflicting attributes. Preferences are used in MAVT. The functional representation of a multi-criteria problem is obtained by aggregating the different single attribute functions, each representing a different attribute, by taking into consideration the relative weights of the attributes. A group utility or value function that takes the diversified evaluations of its individual members into consideration can be obtained either by aggregating individual functions or by partial identification of the group function [5]. Game theory, which is based on utility theory, has been used to study conflict resolution. Recent versions of MAUT/MAVT have tended to look at the broad complexity of a problem within a structured framework and not simply as criteria and alternatives [5]. Detailed reviews of how Bayesian and MAUT/MAVT techniques might be utilized within FAA are presented in section 3.

1.2: OBJECTIVE AND RECOMMENDED APPROACH

The current literature on decision-making based largely on theories and methods is enormous. Despite the development of a large number of refined decision aid methods, none can be considered as the "super method" appropriate to all decision-making situations [6]. There are specific strengths and weaknesses associated with each of the methods. AHP has been among the leading candidates for selection as the decision-making technique for various problems and in most of the cases has been among the top 5 techniques. AHP has been used for hundreds of decision-making problems. AHP could arguably be the most widely used method and hence AHP is selected as the recommended approach for research in this project.

2.: LITERATURE REVIEW ON R&D PLANNING

An extensive review of the literature on R&D Planning was conducted using university and government libraries and electronic search services. Keywords used in the search were:

R&D Investment Analysis
R&D Project Selection
R&D Resource Allocation
R&D Portfolio Selection
R&D Planning Process.

Over 100 project management textbooks or handbooks were reviewed for chapters or sections that dealt with these topics. The following eight journals were found to be the source of the vast majority of articles ever published on these topics:

Operations Research
Management Science
Interfaces
IEEE Transactions on Engineering Management
IIE Transactions
The Engineering Economist
Cost Engineering
Research-Technology Management (formerly Research Management).

The results of our review may be categorized into three broad areas: General (Environment, Processes, and Models); Industrial Applications; Government Applications.

2.1: GENERAL (ENVIRONMENT, PROCESSES, and MODELS)

It is well-recognized that one of the most difficult tasks in any organization is the management of R&D activities. Whether a profit-oriented industrial firm or a mission-oriented government agency, the success of the endeavor in meeting its goals for tomorrow often hinges on the quality of R&D planning, decision-making, and resource allocation done today. In this section we describe generally the state-of-the-art in processes and models to select R&D projects for funding, to decide how much to invest in them initially, and to decide whether to continue their funding in subsequent years.

The R&D environment might very well be the most difficult and turbulent environment in which to manage a project [Kerzner, 1988]. Among the well-documented factors that R&D decision-makers must cope with are:

- Lack of complete information (uncertainty)
- Political pressures that favor one technology over another, one R&D implementer or another, etc.
- Fluctuation in total funding for R&D, year to year

- Unrealistic schedules for and overly optimistic promises on payoff of technology investments
- Communication of priorities from strategic level down to R&D activities may be garbled or ignored, leading to a mismatch between the R&D projects selected (and their investment level) and the strategic needs of the organization.

Bearing in mind the importance of what is at stake and limitations of the information that is normally available, it is no surprise that a vast body of literature addressing the research and development (R&D) project selection problem has developed [Cabral-Cardoso and Payne, 1996]. A number of these articles are listed in the bibliography, focusing mostly on those that appeared the past 15 years. Among the best of the survey articles is Souder [1983], in which he emphasizes that the objective of project evaluation and selection is to identify and screen out inferior projects, permitting only the very best projects to reach the investment analysis (portfolio selection) phase of a three-step process:

Screening
Evaluation
Investment (Portfolio) Analysis.

After indicating that new project ideas spring up from a number of sources, Souder elaborates on the process:

> New project ideas may be temporarily backlogged or put through a screening model. A screening model provides useful preliminary information for distinguishing candidate projects, on the basis of a few prominent criteria. An evaluation model provides a more rigorous and comprehensive analysis of candidates which survive the screening model. A portfolio model can be used to determine an optimum budget allocation among those projects which survive the evaluation model... These three types of decisions may be repeated many times in response to changing information states, changes in the available resources and funds, changes in project achievements, or the arrival of new project proposals.

Screening models have been referred to as a course sieve, that immediately eliminate or postpone clearly inferior projects. Profile models use a few key criteria (e.g., cost, performance, safety) and rate each project as high, medium or low against each criteria. By visually studying the pattern or ratings, superior and inferior candidates emerge. A checklist model is quite similar, but may use criteria scores such as +2=best possible performance, +1=above average performance, 0=average performance, etc. Scores can then be added, or in another technique, Pugh Concept Selection, the pluses are added, the 0's are ignored, and the minuses are added. In weighted scoring, each criterion is assigned a weight (out of a total of 10,100, or 1000) according to its relative importance to the decision authority or agency. These weights are used as multipliers, and a weighted total score for each project may be computed using the criterion scores for that project. Higher scoring projects are favored over lower scoring projects, and a priority ranking is possible.

Evaluation models permit finer distinctions to be made between projects, but require more data. The most widely used evaluation models are called Economic Index models, such as the classic return on investment model which utilizes as input a stream of future benefits ($B_1, B_2, ..., B_n$) and costs ($C_1, C_2, ... C_n$). A ratio of net present worth of benefits to costs is

$$ROI Index = \frac{\sum^{n} Bi/(1+r)^i}{\sum^{n} Ci/(1+r)^i}.$$

In general, these simple models take on the form $\frac{PXR}{C}$ where P is a probability of success, R is a return on investment, and C is the cost. There are many variations on this basic formula [Souder, 1983]. Risk Analysis models produce an entire Arisk profile@ (cumulative probability distribution) on benefit so the decision maker can compare investment opportunities on their total range of return, not just a single expected value. Value Contribution models permit the decision-maker to examine the degree of contribution which a project makes to the organizations hierarchy of goals. Among these models are the multiattribute utility theory (MAUT) model and the analytic hierarchy process (AHP) model. These models deserve serious consideration by the FAA because:

- They are the only models listed so far that permit explicit representation of the value system of the decision authority (e.g., an agency, council, committee);
- They are developed interactively by structured interviews (group or individual), leading to more consensus among participants;
- They are useful in establishing a balanced portfolio;
- They may be used after-the-fact to explain why certain projects were rated high (low);
- They can compensate for incommensurate units in some of the attributes of goal achievement, and force a goal-orientation on all discussions of the value of a project or technology.

Portfolio models belong to the class of constrained optimization models. Under the assumption of an overall budget constraint B and a collection of candidate projects j=1, ..., m with respective costs x_j and value of expenditures $v_j(x_j)$, the problem is to

$$\text{maximize} \sum_{j=1}^{m} v_j(x_j)$$

$$\textit{subject to} \sum_{j=1}^{m} x_j \leq B.$$

More advanced forms exist which include probability of research success with funding level x_j, upper and lower bounds on each x_j, multiple time periods, etc.

It should be noted that only value contribution and portfolio models are useful for resource allocation. Both model types require skill in the development of the model at its parameters, and in interaction with the users to facilitate use of model outputs which typically are used to aid investment decisions, but not to specify an R&D portfolio outright. Yet another caution for FAA in consideration of these model types was cited by [Caffin and Taylor, 1996]: Approaches for project selection do not generally consider project scheduling as part of the selection process. When it is not possible to schedule the selected projects within the desired time frame, projects may be deleted, alternative projects are considered, resources increased, economic goals reduced, or the desired schedule may be relaxed.

Steele [1989], in his text Managing Technology observed that most technical managers feel ambivalent about rigorous project screening techniques. Though they value the use of rigorous, quantitative procedures that reflect the most relevant and valid inputs possible, they recognize large elements of uncertainty in R&D information and are wary of heavy handed or mechanical use of techniques. Steele goes so far as to state despite years of efforts to develop more rigorous program selection techniques, their most noteworthy feature is limited use. These statements should be considered as potentially steering FAA away from the classic portfolio models above and toward a project selection process that is more collaborative and goal-oriented, such as MAUT or AHP.

One interesting study by Cabral-Cardoso and Payne [1996] focused not so much on technique as the roles the techniques play in the process of deciding to select some projects and reject others. They found two main roles: instrumental use relying on the models to guide the decision; supportive use when information gathering and communication processes involved in model development and use are used to support a decision the user wants (often for reasons other than those derived from the solution offered by the model). They noted that in contrast to the wide body of literature on new selection models and techniques, relatively few empirical studies have been reported on the extent to which organizations adopt and use them. We now turn to applications.

2.2: GOVERNMENT APPLICATIONS

In the government and the military, projects develop from ideas in response to mission needs. There are typically a number R&D performers for any given need, some inside the agency or branch, some outside. Project selection in the government can also be greatly influenced by political considerations [Roman, 1986].

Some environmental factors of government agency R&D planning that we have gleaned from assorted publications, both academic and governmental:

- Five-year planning horizon is typical
- Use of projected funding levels, but these are recognized as subject to change
- Many R&D performers, inside and outside the agency
- Variety of contrast and grant mechanisms
- Statutory mission areas
- Division of core competencies among centers, labs
- Congressional direction on spending
- Fluctuations in annual R&D appropriations
- Use of internal committees, subcommittees in evaluation of R&D investment options
- Cooperation with other federal agencies encouraged
- Linkages to agency and line of business strategic and implementation plans.

Roman[1986] has provided a list of characteristics of project selection in government agencies:

> Government projects are subject to an extensive range of technological sophistication, depending on the mission objectives of the authorizing agency.
>
> The determination and authorization of a program are based on need and on mission requirements.
>
> Need, time, and performance are primary considerations.
>
> Cost and value are secondary but important factors [THIS MAY BE QUESTIONABLE IN THE 1990s], and there is little or no concern with immediate commercial applications.
>
> Often the technical concepts involved or hardware delivered is subject to rapid obsolescence, especially in areas where the technology is new or evolving.
>
> Project selection may be closely allied with source selection:
> a. Relatively little in-house work is done by the government
> b. Sponsoring agencies may call for certification of vendors.
>
> The government frequently shifts specifications.
>
> Contractors often make over-optimistic presentations.
> a. They tend to run over original time and cost estimates to complete the project.
> b. They frequently request modification of the original performance specifications.

2.3: INDUSTRIAL APPLICATION

By far the best source found for industrial applications of R&D planning is the journal Research-Technology Management, published by the Industrial Research Institute, a consortium of several hundred top U.S. firms. A secondary source is IEEE Transactions on Engineering Management. We shall organize our discussion into three parts: Best R&D Practices (generally), R&D Metrics, R&D Project Selection & Portfolio Analysis, Case Studies were also found, but have little value to FAA.

Ransley and Rogers [1994] examined four classic studies of R&D practices conducted by the consulting firms Meritus Consulting Services, Pugh-Roberts, SRI International, and Arthur D. Little. Since each study took a different approach to determining best R&D practices, Ransley and Rogers assert that those practices that are common to the four studies provide a strong basis for best R&D practices. Consensus was apparent in the seven categories listed below:

Technology Strategies - Corporate, business, and technology strategies and plans are clear, well-integrated, communicated, and understood across all functions. A common vocabulary is used to characterize technology objectives (e.g., by time frame, risk, approach, market strategy).

Program Selection and Management - Marketing, manufacturing, and planning functions join with R&D in assessing and selecting technology programs. Analytical tools are used to balance the R&D portfolio. Project selection criteria are clearly linked to business strategy. The cross-functional team agrees on project objectives and milestones, and progress is evaluated against these milestones regularly.

Core Strengths – Core technologies are defined and integrated into long-term technology and business plans.

Effectiveness - Results are measured against technology and business objectives.

External Awareness – There is a systematic process for monitoring external threats and opportunities through a variety of sources, such as customers, suppliers, rivals, sales and marketing , universities, government agencies, and industry consortia.

Technology Transfer - Cross-functional teams and job rotation across functions are standard. Management leads in establishing effective, mutually respectful, communication and trust across functions.

Personnel – Career development programs are in place. Recruiting, training, and career development are integrated into the long-term R&D strategy.

Drawing on item 2 above, we can conclude that R&D planning at the FAA should strive to:

A. Include other agency functions in the planning process, especially users of technology.

B. Analytical tools should be considered to assure a balanced R&D portfolio.

C. Project selection criteria should be clearly linked to higher level (strategic) goals and objectives.

D. R&D progress should be measured frequently against project objectives and schedule milestones.

In another benchmarking study, Matheson, Matheson, and Menke identified 45 decision-making practices used by the best of the best, which they assert form a blueprint for doing the right R&D.@ Included in their survey were U.S. Corporate leaders such as 3M, Merck, Hewlett-Packard, General Electric, AT&T, DuPont, and Procter & Gamble, and the new stars, Intel and Microsoft. Overall, executives self-assessment of R&D decision quality had a median of 56 on a scale of 100, indicating a tremendous opportunity for improvement. Interestingly, the most pressing need for improving R&D performance was developing an improved decision process, precisely the problem the FAA feels it has.

The forty-five best decision-making practices were grouped into nine components of decision quality as follows:

- Making Quality Decisions
  -Decision basis - Are inputs to your R&D decisions of high quality?
  -Technology strategy - Is R&D strategy in tune with strategic goals?
  -Portfolio Management - Are your R&D portfolio and pipeline well-balanced?
  -Project Strategy - Is each individual project being managed to its full potential?

- Organizing for Decision Quality

  -Organization and process - Use of a formal development process, organize R&D around major customers, use innovative budgeting mechanisms, etc.

  -R&D culture and values - Do you hire the best people, train them well, and empower them to perform to their full potential?

  -Relationship with internal customer - Does R&D work closely with internal customers?

  -Relationship with end customer - Does R&D look ahead to anticipate and meet needs and desires of the ultimate users of the R&D results?

  -Improving Decision Quality - Learn from post-project audits; measure R&D effectiveness; learn from others.

Some elements within the nine mid-level components that seems to particularly bear upon the FAA's R&D decision-making are:

DB-6 Measure the contribution to strategic objectives
TS-2 Develop a global technology plan
PM-1 Evaluate the R&D portfolio
PM-2 Balance innovations and incremental improvements
PM-5 Hedge against technical uncertainty (first identify and measure it)
PM-6 Manage and prioritize different R&D differently
PS-1 Fully resource projects
PS-4 Evaluate and plan all projects
EC-1 Determine, understand, and measure end customer needs
EC-2 Refine projects using regular customer feedback.

Cooper, Edgett, and Kleinschmidt [1998] state that effective new product development is emerging as the major corporate strategic initiative of the decades ahead ... those that fail will invariably disappear or be gobbled up by the winners. The key issue is how businesses should invest their R&D resources, and Cooper, et al state Many people see portfolio management as the solution ... Portfolio management is a critical topic because it integrates a number of key decision areas, all of which are problematic: project selection and prioritization, resource allocation across projects, and implementation of the business strategy.

Cooper, et al constructed six metrics to capture how well the portfolio of each business surveyed was performing. The results were:

- Businesses, on average, obtain reasonable alignment between their portfolio of projects and the business strategy.

- Portfolios contain moderately-high-value projects, on average.

- Spending breakdowns across projects reflect the business strategy fairly well, on average.

- Project gridlock exists in the project pipeline, with projects not being done on time.

- Businesses tend to lack a balanced portfolio of projects (balance in terms of short term versus long term, high risk versus low risk, and so on).

- Businesses have too many projects underway, give the resources available. Performance on this metric was the weakest of the six.

Of the 105 businesses surveyed, many businesses are performing in a substandard fashion. This would no doubt also be true of government agencies. Two areas where the top 20" corporations really excelled were:

- Portfolio balance

- The right number of projects for the resources available.

Both were areas in which the average business performs fairly weakly.

Managers were found to be not particularly satisfied with their portfolio management approach. The top 20 percent claim more realistic portfolio methods.

Concerning portfolio decision process and methods, the top 20 percent:

- Have an explicit, established method of portfolio management.

- Management buys into the method, and supports it through their actions.

- The method has clear rules and procedures.

- Treats all projects together and considers them as one portfolio.

- Apply the method consistently across all appropriate projects.

It was found by Cooper, et al that the leaders are using a hybrid approach that combines different traditional approaches; they rely far less on financial methods, such as the ROI and payback period methods referred to earlier in this literature review. When these methods are used, they often result in priority ranking of projects or identification of those that meet a predetermined go/kill criteria. So-called business strategy methods are the number one method for the top 20 percent of businesses. Scoring models are used by 12-13% of respondents; bubble diagrams (risk-return plots) by less than 5% of respondents.

In conclusion, Cooper et al show that a method that combines strategy (linkage to strategic objectives, good alignment, and good coverage) models and scoring models would be the best overall method. Again, these findings seem to point toward the AHP or multi-attribute utility theory.

In Cooper, Edgett, and Kleinschmidt [1997], the following important observations are made.

1. Portfolio management has three main goals:

   A. Maximizing the value of the portfolio against the objective, such as profitability (business) or air transport safety and security (FAA).

   B. Balancing the portfolio (many dimensions to consider). Visual models, especially bubble diagrams, help achieve this difficult end.

C. Linkage to strategy. Strategic fit and resource allocation consistent with the business- (agency's) strategy were the key issues here.

2. There is a need to integrate gate decisions and portfolio decisions. Gates are where the senior decision-makes or gatekeepers make go/kill decisions on individual projects, one-by-one; portfolio decisions are usually made on a collective set of potential projects.

3. Portfolio models suffer from imaginary precision. Cooper, et al [1997] cite as a universal weakness of every portfolio model studied the implied degree of precision is far beyond people's ability to provide reliable data.

4. Variable resource commitments is a problem. There seem to be two camps: those who see resource commitments as quite firm; those we see resource commitments as flexible to new situations, new project opportunities, etc.

5. Too many projects are on hold. In lieu of killing good (but not highly ranked) projects, and hurting someone's feelings, projects are dumped into a Hold Tank that may contain many more projects in number than those currently funded.

6. Many companies maintain prioritized lists of projects, but there are again two camps: those that argue that such a list is not only important, but necessary; those that want to use triage on all projects active, on hold, or dead.

7. Portfolio management must consider all types of R&D projects.

8. Should portfolio management models focus on information display or be decision models?

9. Many portfolio models yield information overload.

Three broad or macro goals for Portfolio Management are:

- Value Maximization
- Balance
- Strategic Direction (or linkage).

Value maximization and strategic direction are best achieved by value hierarchies and scoring models; balance, which is better determined after a tentative project portfolio is defined, may best be checked by graphical means.

To conclude this section on Industrial Applications, we note that two articles dealing strictly with R&D metrics were found. In Werner and Souder [1997], an extensive search of the literature from 1956 to 1995 identified over 90 articles, 12 books, and two research reports describing various techniques. Integrated metrics that combine multiple objective and subjective methods were cited as the best approach. It was recognized that integrated metrics are the most complex and costly to develop and use. Werner and Souder state the choice of an appropriate R&D measurement metric depends on the user's needs for comprehensiveness of measurement, the type of R&D being measured, the available data, and the amount of effort the user can afford to allocate to it.

Another article by Hauser and Zettlemeyer [1997] concluded that the best metric for a given situation depend upon the goals of the R, D, & E activity. To classify R&D metrics, they created a tier metaphor:

- Tier 1 - basic research explorations which may have applicability to many lines of business
- Tier 2 - activities that select and develop programs to match or create core technological competence of the organization
- Tier 3 - specific projects focused on the more immediate needs of the customer, business unit, or corporation.

We note that DOD uses R&D classifications 6.1, 6.2, and 6.3 that correspond to Tiers 1, 2, and 3 above. The following table is extracted from Hauser and Zettlemeyer and lists various R&D metrics in use at the companies they interviewed.

Category	Metric	Research Tier Relevance
	Qualitative Judgement	
Strategic Goals	Match to organization's strategic objectives	Tier 2
	Scope of the technology	Tier 2
	Effectiveness of a new system	Tier 2
Quality/Value	Quality of the research	Tiers 1, 2, 3
	Peer review of research	Tiers 2, 3
	Benchmarking comparable research activities	Tiers 2,3
	Value of top 5 deliverables	Tier 3
People	Quality of the quality	Tier 1
	Managerial involvement	Tiers 2, 3
Process	Productivity	Tier 3
	Timely response	Tier 3
Customer	Relevance	Tier 3
	Quantitative Measures	
Strategic Goals	Counts of innovations	Tier 2
	Patents	Tier 2
	Refereed papers	Tiers 1, 2
	Competitive response	Tier 3
Quality/Value	Gate success of concepts	Tier 3
	Percent of goal fulfillment	Tiers 1, 2
	Yield=[(quality*opportunity*relevance*leverage)/overhead]* consistency of focus	Tiers 2, 3
Process	Internal process measures	Tiers 1, 2
	Deliverables delivered	Tier 3
	Fulfillment of technical specifications	Tier 3
	Time for completion	Tier 3
	Speed of getting technology into new products	Tier 3
	Time to market	Tier 3
	Time of response to customer problems	Tier 3
Customer	Customer satisfaction	Tier 3
	Service quality (customer measure)	Tier 3
	Number of customers who found faults	Tier 3
Revenue/Cost	Revenue of new product in 3 years/R&D cost	Tier 3
	Percent revenues derived from 3-5 year-old-products	Tier 3
	Gross margin on new products	Tier 3
	Economic value added	Tier 3
	Break-even value added after release	Tier 3
	Cost of committing further	Tiers 2, 3
	Overhead cost of research	Tiers 1, 2, 3

2.4: AHP LITERATURE REVIEW

A review of the existing literature concentrating on the Analytic Hierarchy Process (AHP) and its applications was carried out. This review revealed that there exist hundreds of recognized publications on AHP and its applications. The extent of research in AHP is exemplified by the fact that entire issues of academic journals have been dedicated to AHP research [24].

Search methodology [25]

Several different approaches were used to search for the relevant information. They are listed below:

1. Database of Engineering Index: This is a major database that contains references to over 5,500 publications related to the engineering disciplines worldwide. This also includes the database of the Compendex Plus. The search was performed with the emphasis on the following keywords: analytic hierarchy process, multi/multiple criteria decision making, multi/multiple objective decision making, expert choice, and group decision making.

2. The University of Alabama Library: The University of Alabama is a member of the Association of Research libraries and has extensive holdings. The card catalog is computerized so that it can be searched for books and journal titles by author, title, subject, or Library of Congress Call number. The following journals were manually reviewed for the period from 1985 to 1998:

    - European Journal of Operational Research
    - Socio-Economic Planning Sciences
    - Mathematical and Computer Modeling

3. Internet search: The resources available on the Internet were searched using the Yahoo!, Alta Vista, Excite, and Lycos search engines. This search was performed using the following keywords: analytic hierarchy process, multi/multiple criteria decision making, multi/multiple objective decision making, expert choice, and group decision making.

Numerous applications of AHP exist in the areas of accounting and finance, architecture and design, capital investment, computers and information systems, conflict analysis, decision support, economics, energy, futures research, group decision making, healthcare, education, long range planning, manufacturing and production, marketing, military, optimization, politics, portfolio selection, public sector and legal planning, regional and urban planning, R & D management, resource allocation, risk analysis, sociology, space exploration, sports and games, surveys of applications, transportation etc. [26]. See Appendix A for a list of successful applications of AHP

One of the major reasons of the emerging popularity of AHP is that the decision maker does not require advanced knowledge of either mathematics or management science to design the hierarchy and to make subjective comparisons of the decision elements. The computational steps are almost always performed on a computer using appropriate software such as "Expert Choice" [27].

Despite or possibly because of its popularity many of the aspects of AHP have become quite controversial. There is an ongoing debate on some of the axioms of AHP. Supporters of some of the traditional areas of decision theory have been particularly critical [27, 28, 29, 30]. An issue that is subject to debate is the calculation of the relative weights. A number of journal articles have debated the relative merits of the eigenvector method versus various least square methods [27, 31, 32, 33]. Recognition of the problem of "information overload" led to the investigation of the modification of AHP that required less data collection. Various measures were introduced to assess judgment accuracy and to decide when to stop the process of pairwise comparisons [34, 35, 36, 37, 38]. Zahir [39] has constructed the vector space formulation of the AHP and has demonstrated that the formulation conforms to the results of the conventional AHP. In this way, he has attempted to lay down the framework for developing a geometric picture of human decision making. Finan and Hurley [40] have argued that, in certain situations, it may be appropriate to calibrate the verbal scale. The result of this calibration is a geometric scale based on a single parameter. They provide limited evidence that the proposed geometric scale marginally outperforms the Saaty 1-9 scale. In another paper, Finan and Hurley [41] have suggested that some artificial perturbation of a decision-maker's final pairwise comparison matrix is likely to enhance the reliability of an AHP analysis. Monsuur [42] has presented a non-probabilistic consistency threshold that is directly related to the relative judgments in the reciprocal matrix. Instead of comparing the inconsistency to the mean performance of a random generator, which can be done irrespective of the decision situation, Monsuur's approach directly confronts the decision-maker with his/her deviation from consistency.

In AHP, a very important concern is to have a rank ordering of the priorities of the decision alternatives [43]. The issue of rank reversal has created a great deal of debate. Researchers have suggested a variety of techniques for dealing with the rank reversal problem. Referenced AHP, normalization to the maximum entry, normalization to the minimum entry, and linking pins are some of the methods that have been proposed to correct the rank reversal problem [27, 30, 44, 45, 46].

Another issue, which often arises in the context of AHP, is to find out whether various groups of individuals giving judgments are alike in judgment or not. In case not all groups of individuals are alike, it is often useful to find out which groups are alike, if any. There are two fundamentally different approaches in AHP: one of them is deterministic and the other statistical or stochastic [43]. Saaty and Basak [47] provide a detailed discussion of these two approaches. It is well known that a shortcoming of the original AHP is its inability to guarantee a consistent rank ordering of the alternatives when identical copies of alternatives are added to the set. That is, the independence of alternatives is not guaranteed and the "Independence of irrelevant alternatives" axiom is violated [48]. A multiplicative variant of the original AHP was proposed which does not suffer from such possible rank reversal [48, 49, 50, 51, 52]. A recent paper [53] has focussed awareness on the group aggregation procedures in the AHP, showing that the multiplicative AHP (which uses the geometric mean aggregation) violates the desirable social choice axiom of Pareto optimality [48]. Honert and Lootsma [48] have argued that this violation can be attributed to the representation used to model the group decision process, thereby questioning the need legitimacy of the Pareto optimality axiom. A geometric mean group aggregation procedure that satisfies the social choice axiom is proposed. Gas and Rapsack [54] have proposed an approach to expert group aggregation based on the "Singular Value Decomposition (SVD)" of AHP pairwise comparison matrices. According to this approach, the group decision phase should consist of the aggregation of the individual expert weight vectors determined by SVD, taking the voting powers of the experts and sensitivity analysis into account based on the Bridgman's principle. In another paper [55] it is argued that in situations which require the determination of the preferences of a group as a whole, unless there is an acceptable level of group consensus, it is premature to use mathematical techniques to generate "consensus" preference vectors. Hence it is necessary to assess the current level of group consensus before applying mathematical techniques to generate a "consensus" preference vector. The possibilities that could result from the use of consensus relevant information embedded in the preference data that arise in the group decision making context are explored. A set of similarity measures and consensus indicators for assessing the level of group consensus that could also be used by the group facilitator to develop strategies for increasing the level of group consensus are offered.

In an arguably definitive work, Peniwati and Forman [56] have stated that individual judgments can be aggregated in different ways. Two of the methods that have been found to be the most useful are the "Aggregation of Individual Judgments (AIJ)" and "Aggregation of Individual Priorities (AIP)". It is proposed that the choice of the method depends on whether the group is assumed to act together as a unit or as separate individuals and it is argued that AIJ is appropriate for the former while AIP is appropriate for the latter. The rationale provided is that in the former case, the geometric average of individual judgments (AIJ) satisfies the reciprocity requirement, implying a synergistic aggregation of the individual preferences in such a way that the group becomes a new "individual" and behaves like one. Individual identities are lost with every stage of aggregation and the Pareto principle is irrelevant. When group members act as individuals (AIP), one could take either a geometric mean (representing an average ratio) or an arithmetic mean (representing an average interval) of their resulting priorities. It is argued that though the Pareto principle will not be violated in either case, the geometric mean is more consistent with the meaning of both judgments and priorities in AHP. If the group members are not considered to be of equal importance, a weighted geometric mean can be used with AIJ or weighted geometric or arithmetic mean with AIP. A separate hierarchy can be constructed to derive priorities of the decision-makers. There is great flexibility in determining who makes the judgments for this hierarchy. When the original group members themselves make these judgments, the eigenvector method, proposed by Ramanathan and Ganesh [53], can be used provided the relative importance of the decision-makers in aggregating to obtain the decision-maker's priorities is assumed to be the same as the priority of the decision-makers in aggregating the priorities of the hierarchy of the original problem [56].

AHP researchers have several choices when constructing AHP instruments that elicit judgments from participants. However little guidance is available regarding the "best" choice. In particular, the AHP response scale can be numerical, verbal, or graphical. Paired comparisons can be presented in a random or nonrandom format, or in a top-down or bottom-up order. Webber et al. [24] have conducted laboratory experiments investigating whether differences in the scale used or format order of paired comparisons yields significant differences in the AHP models.

In most situations, the decision-maker's comparisons will contain a degree of uncertainty. The concept of "judgmental uncertainty" was put forth by Saaty [58] and later elaborated by Vargas [59] by treating the pairwise comparisons as random variables [57]. Zahedi identified two sources of this "judgmental uncertainty". One is the "External source" referring to the procedure or environment for collecting preference data, and the other is the "Internal source" which is due to the limited amount of information available to the decision-maker and his or her understanding of the problem. Both sources of uncertainty can lead to rank reversals and weaken the decision-maker's confidence in the results of the AHP [57, 60]. Saaty and Vargas [61] analyzed the effects of these judgmental uncertainties within the framework of the AHP using an interval approach. This approach assumed that all points within the interval for each pairwise comparison were equally probable. They also computed the probability of a rank reversal affecting the best choice [57]. Zahir [62] has also investigated how judgmental uncertainty can be incorporated within the AHP framework. In this work, uncertainty was introduced as a concept independent of consistency [62]. Bryson and Mobolurin [63] present an action learning evaluation procedure (ALEP) that accommodates ambiguity on the part of the decision-maker. This procedure provides a structure for prioritizing and synthesizing the interval preference scores in an ambiguous decision domain. Rosenbloom [27] provides a probabilistic approach to test the statistical significance of the final scores. Haines [64] has developed a statistical approach to the analysis of interval judgments in the AHP, which involves adopting an appropriate distribution for the weights on the feasible region specified, by those judgments. Honert [65] has proposed a group preference model that expresses the group's preference intensity judgments as random variables with associated probability distributions and exploits the structure of the multiplicative AHP to derive interval judgments for the alternatives' final impact scores as perceived by the group. Paulson and Zahir [57] have reexamined the uncertainty in decision alternative rankings and the probability of a rank reversal as functions of the number of alternatives and hierarchy depth. They followed the traditional "scientific" approach to experimentation [66]. They have analyzed the effect of the various factors considered by them, namely, the number of levels in a hierarchy, the size of the pairwise comparison matrix, and uncertainty on the aggregate measure proposed by them and on the probability of rank reversal individually. They have varied each factor under study over their selected range while maintaining all the other factors constant.

2.5: SUMMARY OF LITERATURE SEARCH

Despite the development of a large number of refined decision aid methods, none can be considered as the "super method" appropriate to all decision-making situations [6]. There are specific strengths and weaknesses associated with each of the methods. Care and judgment must be used in selecting an appropriate method for a specific application. Generally, not all methods applicable to a specific decision situation generate similar solutions. Early in the evolution of the decision-making methods the application of selection techniques for these problems was not considered. Now, it is clear that consequences of mismatches include the possibility of sub-optimal results, discarding of useful models due to improper application, and finally it may discourage potential users from applying these techniques to real world problems [10]. The problem of selecting the most appropriate technique is in itself a decision problem. Researchers have investigated the problem of choosing a model to best suit a decision problem and there are a number of models to assist both the analyst and the decision-maker to select the best method to be used [10].

There exist hundreds of recognized publications on AHP and its applications. Despite or possibly because of its popularity many of the aspects of AHP have become quite controversial. There is an ongoing debate on some of the axioms of AHP. Calculation of the relative weights, information overload, rank reversal, group preference aggregation procedures, and incorporation of judgmental uncertainty have been the more popular research problems. It is believed that there has been extensive and conclusive work done on most of these problems. However, there hasn't been any conclusive work on the incorporation of uncertainty in the AHP. It is believed that the work done by various AHP researchers is a sufficient enough background to motivate research that could help the users of AHP to incorporate the uncertainty felt by them. For this work to not be a mere theoretic exercise it is necessary that it help the user during the hierarchic design and evaluation phases of the AHP such that the confidence of the user in the AHP analysis is increased. Paulson and Zahir [57] have examined the uncertainty in decision alternative rankings and the probability of a rank reversal as functions of the number of alternatives and hierarchy depth. However, they have not studied the individual effect of variation in uncertainty on their selected measures in a hierarchy. They have only studied the effect of the different number of levels in a hierarchy. The limitation of their "one-factor" approach [66] is that if there happens to be an interaction of the factor studied with some other factor, then this interaction cannot possibly be observed. Also, this strategy makes limited use of the test data when evaluating factor effects [66]. Also, by the "one-factor" approach it is not possible to obtain a sufficiently accurate mathematical form of the effect of the various factors (independent variables) on the response variable (dependent variable). It is believed that Paulson and Zahir's [57] work can be improved upon and that the results of such a study could be helpful to the user during the iterative process of hierarchic design. This research effort is a first step in the direction. This research would concentrate on studying the effects of the factors and interactions, if any, on the ranking uncertainty through the use of the now proved and accepted methods of designed experiments. Such an approach would not have the limitations identified above and would result in definitive conclusions about the effects of the various factors and interactions on ranking uncertainty.

3. DETAILED DESCRIPTION OF THREE CANDIDATE APPROACHES

3.1: BAYESIAN ANALYSIS FOR FAA– A SIMPLIFIED EXAMPLE

In today's fast-moving technological world, the need for sound, rational decision making by business, industry, and government is vividly apparent. Typically, in Research and Development, one may have to decide whether to invest in a research program or not. The road from need identification, project formulation to a successful regulation is full of uncertainties. In recent years, statisticians, engineers, economists have placed increasing emphasis on decision making under conditions of uncertainty. This area of study has been called statistical decision theory and Bayesian decision theory [8]. This exercise is an effort to illustrate the application of Bayesian Analysis to FAA's "Research Need and RPD prioritization process". To facilitate the presentation, two primary policies have been adopted:

1. Avoid the use of mathematics, unless absolutely necessary.
2. Explain the method through simple examples.

All decision problems have certain general characteristics. The decision problem under study may be represented by a model in terms of the following elements [8]:

1. **The Decision Maker:** The decision maker is responsible for making the decision. Viewed as an entity, the decision maker may be a single individual, committee, company, nation, or the like, e.g. The Directorate, The Sponsor, AVR Management, AS TAT or a group of people from these departments could be the decision maker/s.

2. **Alternative courses of action:** An important part of the decision-maker's task, over which the decision-maker has control, is the specification and description of alternatives. Given that the alternatives are specified, the decision involves a choice among the alternative courses of action. When the opportunity to acquire information is available, the decision-maker's problem is to choose a best information source or sources and a best overall strategy. The alternatives could be,

    a. Allocate the budgeted amount for the project.
    b. Allocate 50% of the budgeted amount for the project.
    c. Do investigative analysis before allocating any money.

3. **Events:** Events are the scenarios or states of the environment not under the control of the decision-maker that may occur. Uncertainty is measured in terms of probabilities assigned to these events, e.g. a project may succeed or fail, the probability of success could be 55% and the probability of failure could be 45%. These probabilities are called **prior probabilities**.

4. **Consequences:** The consequences, which must be assessed by the decision-maker, are measures of the net benefit, or payoff, received by the decision-maker. Consequences are also called payoffs, outcomes, benefits, or losses. A typical

consequence could be, if a project were to be a success, the fatality rate would be reduced by, say, 4%.

One alternative that frequently exists in an investment decision problem is further research or investigation before deciding on the investment. This means making an intensive objective study. It may involve such aspects as a new analysis of the requirements, or possibly studying, anew, future costs for particular alternative [1]. The decision-maker receives information by observing the outcomes of an experiment or an investigative study, e.g., one may conduct an AHP analysis for the "Research need and RPD prioritization process" and conclude that the particular project/s is/are "important" or "not important". Given knowledge of the outcome of an analysis such as this, the probabilities of the project being a "success" or a "failure" would have new values based on the management's assessment of the confidence in the investigation results. The concepts of Bayesian statistics provide a means for utilizing the subsequent information to modify estimates of probabilities and also the economic value of further investigation study. These modified probabilities are called **posterior probabilities**, e.g., probability of a project being a success, given that it is thought to be "important" in the investigative analysis, can be represented by

"p(success | important)" and its value could be, say 0.85.

Let,

$s_1, s_2, \ldots\ldots, s_n$ denote the possible states of the world or events.
$o_1, o_2, \ldots\ldots, o_m$ denote the possible outcomes of the investigation/analysis.

The posterior probability can then be expressed as $p(s_i \mid o_j)$ where $i = 1,2,..,n$; $j = 1,2,..,m$ [1]. In many situations, however, we may be given the prior probabilities for each state of the world, and instead of being given the posterior probabilities $p(s_i \mid o_j)$, we might be given **likelihoods** $p(o_j \mid s_i)$. For each event, the likelihoods give the probability of observing each outcome of the investigation/analysis. To clarify the meaning of likelihoods, suppose that 55 projects that have successes had been previously been analyzed (investigated); of these 55 projects, 51 were evaluated as "important" and 4 were evaluated as "not important". This would enable estimation of,
p(important | success) = 51/55 and p(not important | success) = 4/55.

The steps involved in the application of Bayesian Analysis can be summarized as [1]:

1. Identify the decision maker/s, alternative courses of actions, events, and consequences.
2. Structure the problem; say in the form of a decision tree.
   No explanation of decision trees is provided in this paper. The interested reader is referred to [1], [2], and [3].
3. Determine the joint probabilities of the form $p(s_i \cap o_j)$ by multiplying the prior probability ($p(s_i)$) times the likelihood ($p(o_j|s_i)$).

4. Determine the probabilities of each experimental/investigation outcome $p(o_j)$ by summing up all joint probabilities of the form $p(s_k|o_j)$.
5. Determine each posterior probability ($p(s_i|o_j)$ by dividing the joint probability $p(s_i \cap o_j)$ by the probability of the experimental outcome ($p(o_j)$).
6. Complete the decision tree based on the information obtained in steps 3, 4, and 5.

The above mentioned procedure is illustrated by the way of an example. In this example it is assumed that a decision needs to be made whether an identified project should be included the R & D portfolio i.e. whether the project should be financed or not?

Step 1:
Decision-Makers: A team comprising the AVR Management, Sponsor, Program Manager, AS TAT, and other FAA Management.

Alternative courses of action:

1. Decide whether the project should be included in the R & D portfolio and whether resources should be allocated based on the present knowledge.
2. Start a project on a smaller scale and based on the outcome of this pilot project make the final decision. This small project is henceforth referred to as the "pilot project".
3. Use other detailed methods of analysis such as the Analytical Hierarchy Process; compare this project with the on-going projects and other competing projects and make the final decision based on the outcome of such a study. This study is henceforth referred to as the "Comprehensive study".

Based on past experience, the decision-makers feel that there is more risk involved in directly going ahead with the project, and the least amount of risk involved if a comprehensive study were to be done. This risk measure includes such factors such as financial loss, failure to achieve the required results, delay in achieving the target of 80% reduction in fatality rate by the year 2007. It is assumed that the associated risk has been quantified and could be represented as:

Risk (make decision to include/exclude now) = 0.5
Risk (pilot project) = 0.3
Risk (comprehensive study) = 0.2

The decision makers have decided to use the following measure to choose from the three options:

Measure of evaluation (ME) = Expected fatality reduction / Associated risk
This measure of evaluation has a higher the better characteristic i.e. the option with the highest ME value would be selected.

Some other measure of evaluation could be used. The amount of investment necessary and other resources consumed could be one such measure of evaluation.

Events:

It is assumed that a project can be a success or a failure. It is assumed that prior probabilities associated with these events are:

p(success) = p(s) = 0.55, p(failure) = p(f) = 0.45.

These estimates could be obtained based on past data.

Consequences:

If a project were a success, 5% reduction in the fatality rate would be achieved. If a project were a failure, 0% reduction in the fatality rate would be achieved.

Step 2: -Please refer Figure 1 for the associated decision tree.
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Step 3: ---We have the following prior probabilities:

$p(s) = 0.55$, $p(f) = 0.45$

Based on the management's confidence for the "pilot project" we have the following likelihoods:

$p(S|s) = 0.9$, $p(F|s) = 0.1$, $p(S|f) = 0.3$, $p(F|f) = 0.7$

where,
S = the pilot project is a success, F = the pilot project is a failure

These estimates could be obtained from past data.

The joint probabilities are estimated as follows:

$p(S \cap s) = p(s) * p(S|s) = 0.55 * 0.9 = 0.495$
$p(S \cap f) = p(f) * p(S|f) = 0.45 * 0.3 = 0.135$
$p(F \cap s) = p(s) * p(F|s) = 0.55 * 0.1 = 0.055$
$p(F \cap f) = p(f) * p(F|f) = 0.45 * 0.7 = 0.315$

Based on the management's confidence for the "comprehensive study" we have the following likelihoods:

$p(I|s) = 0.8$, $p(NI|s) = 0.2$, $p(I|f) = 0.3$, $p(NI|f) = 0.7$
where,

I = the project under consideration is important, NI = the project under consideration is not important.

These estimates could be obtained from past data.

The joint probabilities as estimated as follows:
$p(I \cap s) = p(s) * p(I|s) = 0.55 * 0.8 = 0.44$
$p(I \cap f) = p(f) * p(I|f) = 0.45 * 0.3 = 0.135$
$p(NI \cap s) = p(s) * p(NI|s) = 0.55 * 0.2 = 0.11$
$p(NI \cap f) = p(f) * p(NI|f) = 0.45 * 0.7 = 0.315$

Step 4: -We then compute the probability of each outcome:

$p(S) = p(S \cap s) + p(S \cap f) = 0.495 + 0.135 = 0.63$
$p(F) = p(F \cap s) + p(F \cap f) = 0.055 + 0.315 = 0.37$
$p(I) = p(I \cap s) + p(I \cap f) = 0.44 + 0.135 = 0.575$
$p(NI) = p(NI \cap s) + p(NI \cap f) = 0.11 + 0.315 = 0.425$

Step 5:-Then we use Bayes' rule to determine the required posterior probabilities:

The Bayes' rule can be written as [3]:

$p(S_i|X) = (p(X|S_i) * p(S_i)) / p(X)$

where,
S_i = the potential states of nature
$p(S_i)$ = the estimated prior probability
$p(X|S_i)$ = the conditional probability of getting added study results X, given that S_i is the true state.
$(p(X|S_i) * p(S_i))$ = the joint probability of getting X and S_i.
$p(S_i|X)$ = the posterior probability of S_i given that additional study resulted in X

The interested reader is referred to [1] and [2] for further details on Bayes' rule.
In our example, the required posterior probabilities are estimated using Bayes' rule as follows:

$p(s|S) = p(S \cap s)/p(S) = 0.495/0.63 = 0.78$
$p(f|S) = p(S \cap f)/p(S) = 0.135/0.63 = 0.22$
$p(s|F) = p(F \cap s)/p(F) = 0.055/0.37 = 0.15$
$p(f|F) = p(F \cap f)/p(F) = 0.315/0.37 = 0.85$
$p(s|I) = p(I \cap s)/p(I) = 0.44/0.575 = 0.76$
$p(f|I) = p(I \cap f)/p(I) = 0.135/0.575 = 0.24$
$p(s|NI) = p(NI \cap s)/p(NI) = 0.11/0.425 = 0.26$
$p(f|NI) = p(NI \cap f)/p(NI) = 0.315/0.425 = 0.74$

Step 6:

The decision tree in Figure 1 is completed. The backward induction process is used to estimate the probabilities and estimated fatality reduction rates.

The measure of evaluation is estimated for the three options as follows:

Measure of evaluation (ME) = Expected Fatality Reduction/ Associated Risk

$ME_{\text{to include/exclude now}} = 2.75/0.5 = 5.0$
$ME_{\text{pilot project}} = 2.734/0.3 = 9.13$
$ME_{\text{comprehensive study}} = 2.737/0.2 = 13.68$

Since, the "comprehensive study" option has the ME value, this option should be selected by the decision-makers.

In the example considered here, decision making under uncertainty involving discrete random variables was considered. This was done primarily due to the mathematical simplicity involved with discrete variables. Often, to have a realistic representation of the situation in the model, continuous random variables need to be used. Continuous random variable could have been used for, say, the expected reduction in fatality rate. Under such a situation, a project need not be a "success" or a "failure", rather, expected reduction in fatality rate could be assumed to be following, say, normal distribution with a certain mean and standard deviation. In these circumstances, the priori and the posterior estimates of mean and standard deviation could be obtained. This would be a more realistic representation of the situation. Stochastic decision trees could be used to structure the problem.

Bayesian analysis is a mathematically sound method. It can be effectively used in combination with other methods such as the Analytical Hierarchy Process. It can be particularly useful for screening projects or needs. Also, since it enables re-estimation of the associated decision measures, it can be used to make the "Research need and RPD prioritization process" dynamic in nature. It should be used as a supplementary tool to the other sophisticated methods.

3.2: MAUT/MAVA for FAA– A SIMPLIFIED EXAMPLE

The purpose of this exercise is to illustrate the application of utility theory to FAA's "Research Need and RPD prioritization" process. It is felt that this prioritization process is an initial step towards the final goal of "optimal budget allocation", and "installation of an effective, formal decision making procedure" at FAA. No attempt is made to provide the mathematical foundations of the multi-attribute utility theory; rather the interested reader is referred to [1], [8], and [16]. A simple example is considered to serve the purpose of illustrating the nature of problem domains, the steps involved in the application, and the possible conclusions.

In an uncertain world, the responsible decision-maker must balance judgments about uncertainties with his or her preferences for possible consequences or outcomes. This is particularly important when the available resources to achieve the objectives are scarce. In many situations, it is not an individual but, instead, a group of individuals who collectively have the responsibility for making a choice among alternatives. Utility theory is formal technique that helps in this decision process. [1]

Utility theory concentrates on the preference or value side of the problem. The decision-maker encodes his/her preference for the previously identified attributes in his/her utility function. When more than one attribute affects a decision-maker's preferences, the person's utility function is called a **multi-attribute utility function (MAUT)**. The steps ([8],[16]) involved in the application of MAUT are:

- Create a hierarchy of objectives that the decision-maker wants to achieve. Each level in the hierarchy is a means to the next higher level and at the bottom are the measurable attributes against which the alternatives will be compared

  Let,
  x_i = level of attribute i

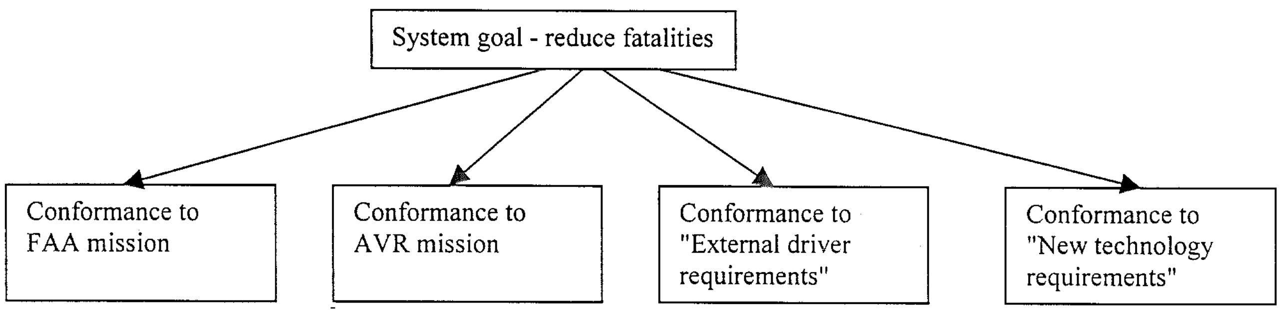
k_i = scaling factor for attribute i
$u_i(x_i)$ = utility associated with level x_i of attribute i
In general, the utility $u(x) = u(x_1, x_2, x_3, \ldots, x_n)$, of any combination of outcomes $(x_1, x_2, x_3, \ldots, x_n)$ for n attributes $(X_1, X_2, X_3, \ldots, X_n)$ can be expressed as either an additive or multiplicative function of the individual functions $u_1(x_1), u_2(x_2), \ldots, u_n(x_n)$ where n is the number of identified attributes.

- Check whether the identified attributes are mutually utility independent
- Assess $u_i(x_i)$ for $i = 1,2,\ldots,n$.
- Determine k_i for $i = 1,2,\ldots,n$.
- Decide on the application of additive or multiplicative utility model
- Check to see whether the assessed utility model is really consistent with the decision-maker's preferences.

It is acknowledged that these steps are not the easiest to understand when expressed in a mathematical form. Hence, these steps will be explained by the way of an example.

This example is with reference to the Figure 3.1 in [16].

Step 1: Organize objectives, attributes, alternatives



Let us say for simplicity purposes that certain needs have been identified. These needs could be "Response to unanticipated events such as smoke in the cockpit", "Fuel dumping in the case of emergency", any previously backlogged need, etc. At the "Requirement process" level the identified needs must be prioritized with respect to conformance to "FAA strategic plan", "AVR mission", "External driver requirements", and "Response to new technologies". These are the identified attributes. The following measure of conformance is used in this example for each of the identified attributes:

9	Absolutely conforms
7	Very strongly conforms
5	Strongly conforms
3	Weakly conforms
1	Very weakly conforms
0	Does not conform

Let,

X_{FAA} = score of conformance of "FAA strategic plan"
X_{AVR} = score of conformance of "AVR mission"
X_{ED} = score of conformance of "External driver requirements"
X_{NT} = score of conformance of "New technology requirements"

Step2: Check whether the attributes are mutually utility independent.
The following question would be asked:
What is the certainty equivalent of a 0.5 chance at the worst X_{FAA} level (0) and a 0.5 chance at the best X_{FAA} level (9), with some other attributes fixed at some level, say, $X_{AVR} = 5$?
Let us say, the decision-maker provides us with the answer $X_{FAA}' = 5$.
Now to check whether the attribute FAA strategic plan is utility independent of AVR mission, the X_{AVR} is fixed at some other level, say 7, and the question is repeated. Suppose the answer was 5 again (or sufficiently close to 5), then the same question is repeated for different levels of X_{FAA}. In an analogous fashion, it can be determined whether AVR mission is utility independent of FAA strategic plan. If FAA strategic plan is utility independent of AVR mission and if AVR mission is utility independent of FAA strategic plan, then FAA strategic mission and AVR mission are mutually utility independent. All the attributes could be treated this way to test for mutual utility independence. Comparing all such possibilities would be a mammoth task. Also, since only two attributes are compared at a time, any higher order interactions would be ignored. The method of designed experiments could be used to decide on the mutual utility independence. An example factorial design is provided below:

Each attribute is considered as a two-level attribute as follows:

Level 1: 0 – does not conform
Level 2: 9 – absolutely conforms

	FAA mission	AVR mission	External drivers	New Technology	Response (Certainty equivalent)
1	0	0	0	0	Y_1
2	0	0	9	9	Y_2
3	0	9	0	9	Y_3
4	0	9	9	0	Y_4
5	9	0	0	9	Y_5
6	9	0	9	0	Y_6
7	9	9	0	0	Y_7
8	9	9	9	9	Y_8

Based on the eight samples of responses $Y_1, Y_2, \ldots, Y_8$, mutual utility independence could be verified. If the response were sensitive to any of the higher order interactions, it would be clear that the attributes are not mutually utility independent. Using this approach, one could obtain the required information by a minimum of eight questions. If one were to study all the possible interactions, it would be possible to obtain the required information by a minimum of sixteen questions.

Admittedly, this procedure is very involved even for small problems. All of the above procedure could be overlooked and the overall opinion of the decision-makers could be used to have a judgment about the mutual utility independence of the attributes. For our illustrative example, it is assumed that the four mentioned attributes are mutually utility independent.

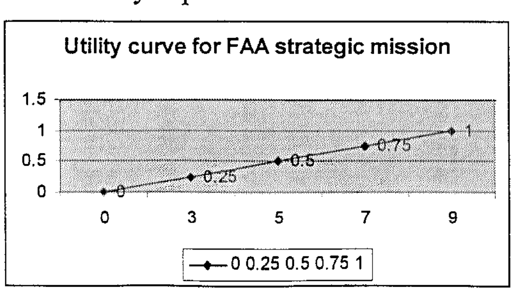
Step 3: Assess $u_i(x_i)$ for $i = 1,2,\ldots,n$. n is the number of identified attributes

In our illustrative example, we have identified four attributes. Hence we need to identify the utility functions for each of the four identified attributes. As a general rule, the worst outcome for each attribute should be assigned a utility of 0, and the best outcome of each attribute should be assigned a utility of 1. The utility function for "FAA strategic mission" could be assessed in the following manner:

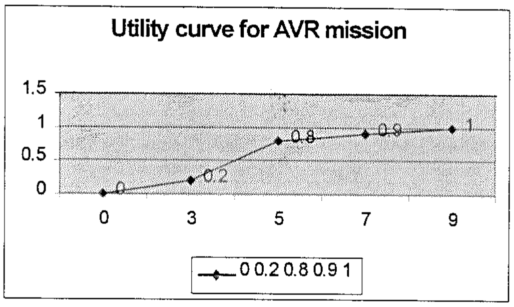
Let,
${}_0X_{FAA}$ = minimum attribute level = 0
${}_*X_{FAA}$ = maximum attribute level = 9
We assign $u({}_0X_{FAA}) = 0$, and $u({}_*X_{FAA}) = 1$
The following questions are then asked of the decision-maker/s:
What certainty outcome, X_{FAA}, would be equally as desirable as a 50% chance of ${}_*X_{FAA}$ and a 50% chance of ${}_0X_{FAA}$?
If the answer is, say 5, the new utility value can be calculated as follows:
Utility of the certain outcome = the probability of the best outcome.
So, in our case, $u(X_{FAA} = 5) = 0.5$
What certainty outcome, X_{FAA}, would be equally as desirable as a 25% chance of ${}_*X_{FAA}$ and a 75% chance of ${}_0X_{FAA}$?
If the answer is, say 3, the new utility value can be calculated as follows:
Utility of the certain outcome = the probability of the best outcome.
So, in our case, $u(X_{FAA} = 3) = 0.25$
What certainty outcome, X_{FAA}, would be equally as desirable as a 75% chance of ${}_*X_{FAA}$ and a 25% chance of ${}_0X_{FAA}$?
If the answer is, say 7, the new utility value can be calculated as follows:
Utility of the certain outcome = the probability of the best outcome.
So, in our case, $u(X_{FAA} = 7) = 0.75$

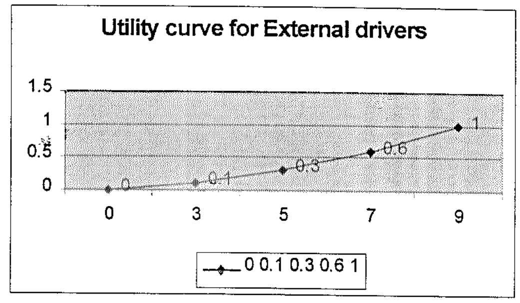
The utility curve of the decision-maker could now be approximated as shown in the graph below.

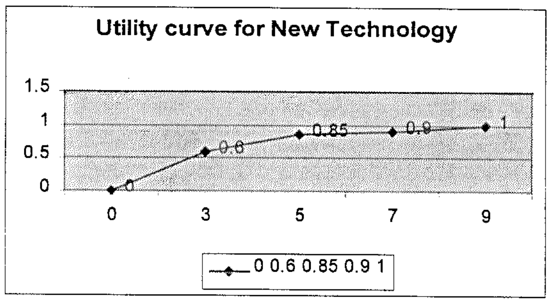
The intermediate points need to be verified until one is satisfied with the accuracy of his or her utility representation.



Similarly the utility curves for the other attributes could be obtained.







Step 4: Determine k_i for $i = 1,2,\ldots,n$. n is the number of identified attributes

The scaling factors for all the four attributes need to be determined. The following question would be asked.

What probability P of all attribute outcomes at their best levels versus probability (1-P) of all attribute outcomes at their worst levels would be as desirable as FAA strategic mission at its best level (i.e. $X_{FAA} = 9$) and all other attributes at their worst levels (i.e. $X_{AVR} = 0$, $X_{ED} = 0$, $X_{NT} = 0$)?

Let us say, the answer to the question is, say, 0.4. Thus the scaling factor for the FAA strategic mission attribute $k_{FAA} = 0.4$.

To determine the scaling factor for AVR mission, the following question could be asked: What FAA mission level, given AVR mission level at its worst (i.e., 0) would be as desirable as what AVR mission level, given FAA mission at its worst (i.e., 0)?

Let us suppose that the answer is:
FAA mission, $X_{FAA}' = 5$
AVR mission, $X_{AVR}' = 8$

The following relation could be now used to find the value of k_{AVR}:

$k_{AVR} * u(X_{AVR}) = k_{FAA} * u(X_{FAA})$

From the utility functions, we get,

$u(X_{AVR}) = u(8) = 0.95$
$u(X_{FAA}) = u(5) = 0.5$
$k_{AVR} = (0.4 * 0.5) / 0.95 = 0.21$

Similarly, one could estimate the scaling factors, k_{ED} and k_{NT}.

Let us say,
$k_{ED} = 0.19$, and
$k_{NT} = 0.2$

Step 5: Decide on the application of additive or multiplicative utility model

We check whether $\Sigma k = 1$.
If $\Sigma k = 1$, the additive utility model should be used.
If, $\Sigma k \neq 1$, the multiplicative utility model should be used.
In the example considered, $\Sigma k = 1$, and hence we use the additive utility model.

Step 6: Check to see whether the assessed utility model is really consistent with the decision-maker's preferences.

A dummy set of alternatives (lotteries) could be used and the utility functions arrived at could be used to rank the alternatives from most favorable to least favorable. The decision-maker could also be asked to rank the alternatives from most favorable to least favorable. If the assessed utility function is consistent with the decision-maker's preferences, the ranking obtained from the assessed utility function should closely resemble the decision-maker's ranking.

The composite utility function can now be represented by,

$$U(X_{FAA}, X_{AVR}, X_{ED}, X_{NT}) = k_{FAA}*u(X_{FAA})+k_{AVR}*u(X_{AVR})+k_{ED}*u(X_{ED})+k_{NT}*u(X_{NT})$$

As an extension to the example, suppose, three needs have been identified. The following information on the outcomes is expected for each attribute.

Attribute	Expected outcomes		
	Need 1	Need 2	Need 3
FAA mission	5	3	5
AVR mission	4	5	6
External drivers	3	3	4
New technologies	2	8	7

These expected outcomes could then be converted to the utility values using the utility curves.

Attribute	Utilities		
	Need 1	Need 2	Need 3
FAA mission	0.5	0.25	0.5
AVR mission	0.5	0.8	0.84
External drivers	0.1	0.1	0.2
New technologies	0.4	0.95	0.9

$U(X_{FAA}, X_{AVR}, X_{ED}, X_{NT}) = k_{FAA}*u(X_{FAA})+k_{AVR}*u(X_{AVR})+k_{ED}*u(X_{ED})+k_{NT}*u(X_{NT})$
$U(X_{FAA}, X_{AVR}, X_{ED}, X_{NT}) = 0.4*u(X_{FAA})+0.21*u(X_{AVR})+0.19*u(X_{ED})+0.2*u(X_{NT})$

For Need 1:
$U(X_{FAA}, X_{AVR}, X_{ED}, X_{NT}) = 0.4*0.5 + 0.21*0.5 + 0.19*0.1 + 0.2*0.4 = 0.404$

Similarly, for Need 2:
$U(X_{FAA}, X_{AVR}, X_{ED}, X_{NT}) = 0.477$

Similarly, for Need 3:
$U(X_{FAA}, X_{AVR}, X_{ED}, X_{NT}) = 0.59$

This means that the needs are ranked in the following order:

1. Need 3
2. Need 2
3. Need 1

These ranked needs could act as a guideline to AS TAT, R,D & E division, and the overall "Research process". It is felt that these needs could be broad based at the "Requirements process" stage, but the terminology involved would need to be developed/modified at the R, D & E Division level to suit the development of particular RPDs and facilitate their prioritization. It is also felt that at the operational level the attributes need to be more.

The procedure used to prioritize needs is used below to prioritize RPDs. The identified attributes are, say,

Potential to reduce accidents (measured on a scale from 0 to 9)

Potential to reduce incidents (measured on a scale from 0 to 9)
Cost impact on affected parties (measured on a scale from 0 to 9)
The scales used are such that higher the number, better would be the attribute. This would mean that for the "Cost impact", higher the number, lesser would be the cost impact on affected parties. It is assumed that these attributes are mutually utility independent.

Attribute	Expected outcomes		
	RPD 1	RPD 2	RPD 3
Accident	8	7	4
Incident	4	3	8
Cost impact	6	2	3

These expected outcomes could then be converted to the utility values using the utility curves. In this case, the utility values are assumed.

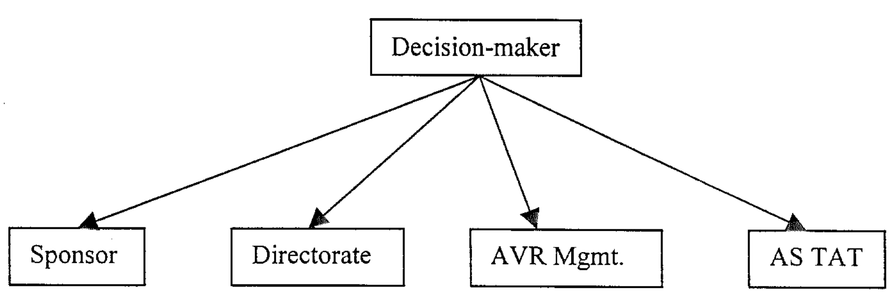
Attribute	Utilities		
	RPD 1	RPD 2	RPD 3
Accident	0.88	0.75	0.8
Incident	0.35	0.35	0.56
Cost impact	0.56	0.22	0.44

$U(X_A, X_I, X_{CI}) = k_A*u(X_A)+k_I*u(X_I)+k_{CI}*u(X_{CI})$

The scaling factors are also assumed as follows:
$k_A = 0.5$, $k_I = 0.3$, $k_{CI} = 0.2$
For RPD 1, $U(X_A, X_I, X_{CI}) = 0.66$
For RPD 2, $U(X_A, X_I, X_{CI}) = 0.52$
For RPD 3, $U(X_A, X_I, X_{CI}) = 0.66$

This means that, RPD 1 and RPD 3 are more important than RPD 2. This prioritization could be then used for the resource (budget) allocation.

Most of the decisions involved in the FAA's context are group decisions. Utility theory can be used to arrive at group decisions. Please refer to the following diagram for an illustration of the application of utility theory to group decision making.



In the prioritization of needs, various different organizations are involved. The utility function for the final decision, could be expressed as a function of the utility functions of the different organizations and individuals. The form of the utility function is,

$$U(\mathbf{X}) = U_D(u_1(\mathbf{X}), u_2(\mathbf{X}), u_3(\mathbf{X}), \ldots.., u_n(\mathbf{X}))$$

where **X** represents the vector of the consequences or outcomes and n represents the number of individuals and groups involved in decision making. The method used for prioritizing needs and RPDs could be used to arrive at the final decision based on the utility functions of the different individuals and the groups involved.

The MAUT is the one of the more cumbersome methods. But, it can be used to formalize the decision making process at FAA. Using MAUT, it is possible to capture the "political" nature of the situation. The roles played by the different organizations and individuals could be incorporated in the decision making process. The method is mathematically more sound than most of the competing methods. Also, it would be possible to incorporate the decision making skills of proven leaders at FAA in the formal decision making process. But, as has been pointed out by Keeney and Raiffa, "The methodology is highly subjective, counterintuitive for a practitioner, and frustrating for the analyst."

Peniwati [5] has concluded that for "Group decision-making", AHP is the best of the available methods. Also, in other such studies AHP has been among the leading candidates for selection and in most of the cases has been among the top 5 techniques. Saaty [18] states that any decision-making method should be simple in construct, adaptable to both groups and individuals, natural to the human intuition and thinking, encourage compromise and consensus building, and not require inordinate specialization to master. AHP satisfies all these requirements and this explains why AHP has been used for hundreds of decision-making problems. AHP could arguably be the most widely used method and hence AHP is selected for further study and research in this project.

3.3: ANALYTIC HIERARCHY PROCESS (AHP) IN DETAIL

The AHP is a theory of measurement for dealing with quantifiable and/or intangible criteria that has found rich applications in decision theory. It is based on the principle that, to make decisions, experience and knowledge of people is at least as valuable as the data they can use [21]. This theory had its beginnings in the fall of 1971 while the originator of this theory, Dr. T. L. Saaty, was working on the problems of contingency planning for the Department of Defense. The application maturity of the theory came with the Sudan Transport Study in 1973 [19]. Since, its introduction, the AHP has found its way into various decision areas. As a technique not firmly rooted in utility theory, AHP, during the initial decade, remained outside the mainstream of decision analysis research. However, the practical nature of the method, suitable for solving complicated and elusive decision problems, has led to applications in highly diverse areas and has created a voluminous body of literature [22].

Decision applications of the AHP are carried out in two phases: hierarchic design and evaluation [21]. The hierarchic design is probably the most important aspect of the AHP [22]. A hierarchy is a particular type of system, which is based on the assumption that the entities, which are identified, can be grouped into disjoint sets, with entities of one group influencing the entities of only one other group, and being influenced by entities of only one other group [19]. At the top of the hierarchy lies the most macro decision objective, such as the objective of making the best decision (or selecting the best alternative) [22]. This macro objective is also termed as the "Goal". The lower levels of the hierarchy contain attributes (objectives) that contribute to the quality of the decision. Details of these attributes increase at the lower levels of the hierarchy. The last level of the hierarchy contains decision alternatives or selection choices [22]. The elements in each group (also called level, cluster, stratum) of the hierarchy are assumed to be independent [19]. If there is dependence among them the method provided by Saaty [19] could be used to study dependence and independence separately and then combine the two. The design of hierarchies requires experience and knowledge of the problem area. Two decision-makers would normally structure two different hierarchies of the same problem. Thus, a hierarchy is not unique. On the other hand, even when two people design the same hierarchy, their preferences may yield different courses of action. However, a group of people can work together to reach consensus on both the hierarchy (design) and on the judgments and their synthesis (evaluation). The hierarchic design phase of the AHP implementation involves three nonsequential interrelated processes: level and element identification, concept definition, and question formulation [21]. In the first step, levels and elements (concepts) within levels are identified. They are then defined and used in the question formulation phase. If the decision-maker has a problem answering these questions, then the levels and the concepts must be revised and modified [21]. Perhaps the most creative task in making a decision is to choose the factors that are important for that decision [23]. Hence it is appropriate that hierarchic design be an iterative process where the concepts, the questions to be answered and the answers associated with the questions, determine the elements and the levels of the hierarchy. Because ambiguities in the questioning process may lead the decision-maker to select the wrong criteria or alternative, all questions should be answerable and consistent with the existing information [21]. Saaty [19] provides the following list of the advantages of hierarchies.

1. Hierarchical representation of the system can be used to describe how changes in priority at upper levels affect the priority of elements in the lower levels.

2. They give great detail of information on the structure and function of a system in the lower levels and provide an overview of the actors and their purposes in the upper levels. Constraints on the elements in a level are best represented in the next higher level to ensure that they are satisfied. For example, nature may be regarded as an actor whose objectives are the use of certain material and subject to certain laws as constraints.

3. Natural systems assembled hierarchically, i.e. through modular construction and final assembly of modules, evolve much more efficiently than those assembled as a whole.

4. They are stable and flexible; stable in that small changes have small effect and flexible in that additions to a well-structured hierarchy do not disrupt the performance.

The evaluation phase is based on the concept of paired comparisons. The elements in a level of the hierarchy are compared in relative terms as to their importance or contribution to a given criterion that occupies the level immediately above the elements being compared. The decision maker translates the available information into paired comparisons by answering questions such as: Given a criterion and two alternatives A and B, which alternative satisfies it more and how much more? This results in a matrix of pairwise comparisons [21]. Saaty [19] provides a scale and recommends it for the pairwise comparisons. This scale is summarized in Table 1.1. When compared with itself, each element of the pairwise comparison matrix has equal importance. Therefore diagonal elements of the pairwise comparison matrix always equal one. Also, the lower triangle elements of the matrix are the reciprocal of the upper triangle elements. Thus, pairwise comparison data are collected for only half of the matrix elements excluding the diagonal elements [22]. "n*(n-1)/2" pairwise comparisons are required when the size of the square pairwise comparison matrix is "n". The comparisons are performed for the elements in a level, with respect to all the elements in the level above.

The solution technique of the AHP takes in as input the above pairwise comparisons and yields a relative scale of measurement of the priorities or weights of the elements. That is, the scale measures the relative standing of the elements with respect to a criterion independently of any other criterion or element that may be considered for

TABLE 1: THE SCALE IN AHP [19]

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between adjacent scale values	When compromise is needed
Reciprocals of the above nonzero numbers	If activity "i" has one of the above nonzero numbers assigned to it when compared with activity "j", then "j" has the reciprocal value when compared with "I"	A reasonable as assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining "n" numerical values to span the matrix

comparison. These relative weights sum to unity. This can be accomplished by using the principal right eigenvector of the matrix of paired comparisons. The elements of each column of the pairwise comparison matrix are added and each entry in the column is divided by the total of the column. The entries in the rows are then averaged to obtain the priority vector. This priority vector is an estimate of the principal right eigenvector of the matrix of paired comparisons. This vector satisfies the following relation:

$$A\,w = \lambda_{max}\,w$$

where A is the observed matrix of pairwise comparisons, λ_{max} is the largest eigenvalue of A, and w is the right eigenvector. Saaty [19] has shown that λ_{max} is always greater than or equal to n. The closer the value of λ_{max} is to n, the more consistent are the observed values of A. This property has led to the construction of the consistency index (CI) as [19, 22]

$$CI = (\lambda_{max} - n)/(n-1)$$

and of the consistency ratio (CR) as [19, 22]

$$CR = (CI/ACI) * 100$$

where ACI is the average index of randomly generated weights [19]. Saaty [19] mentions that it is possible that reality could be inconsistent and presence of consistency is no proof of the modeling of reality. However, as a rule of thumb, a CR value of 10 percent or less is considered acceptable. Otherwise, it is recommended that A be reviewed to resolve inconsistencies in the pairwise comparisons [22].

The final ratings (or global weights) of the elements at the bottom level of the hierarchy in achieving the most general objective of the problem are obtained by aggregating the relative weights of the various levels. If W' is the priority vector of the p^{th} level with respect to some element z in the $(p-1)^{st}$ level, then the priority vector W of the q^{th} level ($p < q$) with respect to z is given by [19]

$$W = B_q * B_{q-1} * \ldots\ldots\ldots * B_{p+1} * W'$$

This relation can be used to obtain the global weights of the elements at the bottom level of the hierarchy relative to the overall objective or goal. While there is an infinite number of ways of synthesizing the weights of the criteria, this additive aggregation rule has the advantage of intuitive understanding of the apportionment of the whole into its parts [21].

The areas in which AHP is applied are diverse and numerous. Nevertheless, they share a set of common features. Majority of the cases are decision problems that involve rating decision alternatives for evaluation, selection, or prediction. Almost all cases involve some qualitative, as opposed to quantitative, elements that play an essential role in decision problems [22]. Most real-life cases are complex in that they involve a host of interrelated elements with varying degrees of impact on the decision.

The Analytic Hierarchy Process has been applied in a variety of areas as a useful and practical multi-criteria decision analysis tool. In the AHP, a decision process is modeled as a hierarchy. At each level in the hierarchy, the decision-maker is required to make pairwise comparisons between the decision alternatives and criterion using a ratio scale. The AHP then determines the relative ranks of the decision alternatives. The ranks of the decision alternatives are given by the elements of the normalized right-hand eigenvector of a preference matrix consisting of the pairwise comparisons between alternatives [57].

In most situations, the decision-maker's pairwise comparisons will contain a degree of uncertainty [57]. If there is uncertainty either in the judgments of the criteria, or in the judgments of the alternatives, or both, the uncertainty is perpetuated to the scales and thus to the final outcome. One would be inclined to think that there should be no concern if uncertainty leaves the rank of the alternative chosen unchanged. However, this is not true. Even if the rank stays the same, the decision-maker may have little confidence in his judgments. In these situations one would need a measure of the uncertainty to decide whether it would be wise to proceed with the best choice or more information is needed to remove some or all of the uncertainty [61].

3.4 ADDITIONAL AHP DETAILS

There are fundamentally two different approaches in AHP. One of them is deterministic and the other statistical or stochastic in nature. Basak and Saaty [47] provide a detailed discussion of these approaches [67]. The deterministic AHP requires the decision-maker to make subjective point estimates for the elements in the pairwise comparison matrix. In the statistical or stochastic AHP, the elements in the pairwise matrix are treated as random variables. Various AHP researchers have used this approach, particularly, in the analysis of judgmental uncertainty. The concept of "judgmental uncertainty" was put forth by Saaty [58] in the late seventies and was later elaborated by Vargas [59] by treating the pairwise comparisons as random variables. Zahedi [60] identified two sources of uncertainty. "External sources" of uncertainty that refer to the procedure or environment for collecting preference data. "Internal sources" are the ambiguity and the uncertainty that result from the limited amount of information available to the decision-maker and the level of his or her understanding of the problem. Both sources of uncertainty can lead to rank reversals and weaken the decision-maker's confidence in the results of the AHP.

Saaty and Vargas [61] classify the uncertainty as:

a) Uncertainty about the occurrence of events, and
b) Uncertainty about the range of judgments used to express preferences

They also mention that the first type is beyond the control of the decision-maker whereas the second type is the consequence of the amount of information available to him/her and his/her understanding of the problem. Saaty and Vargas [61] analyzed the effects of the uncertainty of the second type within the framework of AHP using an interval approach.

This approach assumed that all points within the interval for each pairwise comparison were equally probable. They obtained the maximum, minimum, average, and standard deviations of each element of the eigenvector using a sample of 100 simulated matrices. They also computed the probability of rank reversal affecting the best choice. To investigate uncertainty in the case of a hierarchy, Saaty and Vargas [61] outline the mechanism analytically how the uncertainty affects the ranks of the decision alternatives. Although, they illustrate the idea by an example with a hierarchy of two levels, their idea is applicable to a hierarchy of any number of levels. Their approach is an approximation only applicable if the uncertainties are small. It is their argument that if a decision-maker states that all entries of the pairwise comparison matrices fall between 1/9 and 9 (the widest range of values used to represent the judgments), the probability of rank reversal among all activities would be equal to unity. However, if the judgments are tightly distributed around a value (i.e. the length of the interval is relatively small) then the probability of rank reversal should converge to zero as the length of the interval converges to zero. Conversely, large ambiguity in the judgments can render ranking a useless pursuit.

Zahir [62] has also investigated how judgmental uncertainty can be incorporated within the AHP framework. In this work, uncertainty was introduced as a concept independent of the notion of consistency. Zahir [62] developed an algorithm and computational procedures to calculate the resulting uncertainties in the relative priorities of the decision alternatives. The analytic approach is approximate to the first order and suitable for comparison matrices of smaller dimension ($n \leq 4$). The numerical approach is more exact and of higher computational complexity. However, the methodology of Zahir [62] has the following limitations [57]:

a) Direct enumeration of all possible combinations of uncertainties of the elements in the preference matrices is required. Hence, the algorithm is of high combinatorial complexity and is difficult to apply in practice.

b) Rank uncertainty is computed independently at each level of the decision hierarchy and then combined algebraically for the whole hierarchy using a maximum possible error approach. This results in overestimates of the rank uncertainties.

c) There is no consideration of the probability distribution underlying the judgmental uncertainties.

Paulson and Zahir [57] have revisited the analysis of uncertainty using a simulation technique. In their work, they adhere to the original axioms of AHP [19] with one exception: they assume a continuous ratio scale from 1 to 9 for the preference matrices to enable the observation of the measures used over a wide range of uncertainties (between 2% and 20%). The probability of rank reversal is the likelihood that the ranks of any two alternatives may be reversed as a result of uncertainty in the pairwise comparisons. This statistic is of little practical value in most decision situations. Decision-makers would be usually more interested in the probability that the rank of the dominant alternative might change. The common assumption is that this probability is proportional to the probability of a rank reversal. However, in their research, Zahir and Paulson [57] have introduced an aggregate measure of the uncertainty in the eigenvector. This measure reflects the level of confidence of the decision-maker in the ranks determined by the AHP whether or not there is a chance of rank reversal. They have analyzed the effects of judgmental uncertainty within the AHP in the following ways:

a) For a single level hierarchy

   i) varying judgmental uncertainty and keeping the dimension of the matrix fixed
   ii) varying the dimension of the matrix and keeping uncertainty fixed

b) For a multi-level hierarchy

   i) varying the number of levels in the hierarchy, keeping the dimension of the matrices and the uncertainty constant

Planning FAA's Resource Allocations to Research and Development Projects

4. RECOMMENDED APPROACH FOR PLANNING R&D ALLOCATIONS

The purpose of this section is to describe a general approach for applying the leading candidate(s) solution technique, namely the AHP, and associated to the focused FAA R&D investment problem. It is envisioned that this approach would eventually serve as the framework, in a detailed follow-on research, for actually enumerating a recommended most effective portfolio of R&D projects. This approach will be depend on using a combination of the results and information obtained in the problem definition phase and the AHP solution methodology. The recommended approach that is as described below.

First, information obtained from the problem definition task such as the selected division's primary goal(s), sub-goals or objectives and operational requirements as well as the current and planned allocation of these requirements to technology strategies are asserted. It is anticipated, that this information, which represents the present organizational planning, will then be projected into the future to predict likely logical future states of the system. Somewhere between five and ten years would be the most likely prediction horizon. These future states would be defined in terms of measures of effectiveness related to degree of satisfaction of organization goals. To effectively accomplish this other information concerning affected parties, political and social considerations and forecasts of future technology options will also have to be made available to the prediction process. Selected auxiliary solution tools will be evaluated for making such predictions.

Second, methods such as the Analytic Network Process (ANP) will be used to determine a more effective allocation of operational requirements to technology. That is, AHP (ANP) will be evaluated as to their potential to determine a more effective, if any exist, allocation of operational requirements to technology strategies. It is assumed that the logical future states corresponding to any such possible reallocation would be derived.

Third, a backward (chronologically) process will be developed starting with the desired future (most likely between five and ten years from the present) state of the system. Such a process would employ a solution methodology capable of determining what policies, affected parties attitudes and technology options would have to be to make the desired future state most likely. Upon comparing this backward process with the derived logical future(s) The ANP solution methodology, that is capable of determining how we should attempt to control or steer the logical future process based on our desired future state will be applied.

Appendix E contains a detailed outline of these recommendations as presented to FAA.

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APPENDIX A

SUCCESSFUL AHP APPLICATIONS

SUCCESSFUL AHP APPLICATIONS IN

CORPORATE EXECUTIVE DECISION MAKING

Strategic Planning
Acquisitions
Mergers
Research & Development
Marketing
New Product Development
Product Life Cycle Analysis
Capital Acquisitions
Investment Analysis

CORPORATE MANAGERIAL DECISION MAKING

Advertising
Public Relations
Employee Evaluation or Promotion Decisions
Hiring or Reduction in Force (RIFS)
Proposal Planning
Marketing
Purchasing or Buy/Lease

SMALL BUSINESS

Strategic Planning
New Products
Product Life Cycle
Advertising
Bid/No Bid on Request for Proposal (RFP)
Sue/Don't Sue & Settle/Don't Settle
Time Allocation
Hiring/Firing

NATIONAL POLICY

Strategic Planning
Nuclear Arms Limitation Agreements
Budget Allocation
National Crisis
Support/Oppose Legislation
Proposal Planning
Military Decisions

PUBLIC ADMINISTRATION (FEDERAL, STATE, & LOCAL)

Resource Allocation
Policy Decisions
Evaluating Requests for Proposals (RFP'S)
Practical Planning
Legal Decisions
Budget Allocation

APPENDIX B

GROUP DECISION MAKING WITH AHP

GROUP DECISION MAKING WITH AHP

Note to Reader: *The following material comes from the Expert Choice software users manual (Reference [17]). Since Expert Choice is a software implementation for AHP the reader can consider AHP and Expert Choice as synonyms in the following discussion.*

INTRODUCTION

Expert Choice (EC) is ideal for group decision making. In fact, brainstorming and sharing ideas and insights (inherent in the use of Expert Choice in a group setting) often leads to a more complete representation and understanding of the issues.

There are several approaches to using Expert Choice in group decision making. The approach that works best depends on the particular group and the decision being contemplated. An approach that works well for a group with "common" interests may not work very well for a group with conflicting interests.

Group decisions involving participants with common interests are typical of many organizational decisions. Even if we assume a group with common interests; however, individual group members will each have their own motivations and hence will be in conflict on certain issues. Nevertheless, since the group members are supposed to be striving for the same goal and have more in common than in conflict, it is usually best to work as a group and attempt to achieve consensus. This mode maximizes communication as well as each group member's role in the decision.

An interesting aspect of using Expert Choice is that it minimizes the difficult problem of "groupthink" or dominance by a strong member of the group. This occurs because attention is focused on a specific aspect of the problem as judgments are being made, eliminating drift from topic to topic as so often happens in group discussions. As a result, a person who may be shy and hesitant to speak up when a group's discussion drifts from topic to topic, will feel more comfortable in speaking up when the discussion is organized and attention turns to his area of expertise.

Since Expert Choice reduces the influences of groupthink and dominance, other decision processes such as the well known Delphi technique may no longer be attractive. (The Delphi technique was designed to alleviate groupthink and dominance problems. However, it also inhibits communication between members of the group. If desired, Expert Choice can also be used within the Delphi context.)

When Expert Choice is used in a group session, the group can be shown a hierarchy that was prepared in advance. The group defines the issues to be examined and alters the prepared hierarchy or constructs a new hierarchy to cover all the important issues. A group with widely varying perspectives can feel comfortable with a complex issue when the issue is broken down into different levels. Each member can present their own concerns and definitions. Then the group can cooperate in identifying the overall structure of the issue. In this way agreement can be reached on the higher-order and lower-order objectives of the problem by including all the concerns that members have expressed.

The appearance of priorities on the screen may distract new users in the early stages of modeling. As new judgments alter the defaults, the more argumentative users may use the priorities they see as a means to sway the results in favor of their own biases. Therefore, the priorities at each redraw can be usefully suppressed by setting the display of the priorities to "neither" in the User Setup.

USING THE GEOMETRIC MEAN TO COMBINE GROUP JUDGMENTS

The group would then provide the judgments. If during the process it is impossible to arrive at a consensus on a judgment, the group may use some voting technique, or may choose to take an "average" of the judgments. In the latter case individual judgments can be combined on a pocket calculator, or by using the internal EC calculation (see Group Judgments under the Numerical Judgment Mode) by computing what is called the geometric mean, as follows: the judgments provided by n individuals are multiplied and the nth root of the product is extracted. For example, the geometric mean of the four numbers 3, 6, ½ and 7 is the 4^{th} root of (3 x 6 x ½ x 7) or 2.8. The multiple judgments are put into cells in the Numerical Comparison Mode. It is not necessary to put the same number of judgments in each cell. If the group has consensus on a judgment, input that judgment only.

Tip: When working with groups and taking the geometric means of their judgments in the numerical mode, and for some judgment the suggested judgments are far apart, it may be useful to try first one judgment, then the other, to find which yields a higher consistency with the rest of the judgments.

COMBINE GROUP JUDGMENTS IN RATINGS

It is also possible to enter group judgments in the EC ratings spreadsheet. In this case the judgments are averaged arithmetically.

Another approach to consider when consensus is difficult to achieve is to have each group member make all the judgments in their own copy of the model and then combine the results. The combining can be achieved in several ways.

The first method to combine individual judgments is to structure an EC model where the group members are the players at the top level of the tree.

First, each group member would make judgments on his or her part of the model. Then, before a synthesis is performed, it must be decided how much weight to give each group member. The group may decide to give them equal weight, or the group members could cooperate to weight their relative importance in Level 1 of the EC tree. For example, the group members: president, first vice president, and so on, appear in the first level under the goal. By assigning priorities to these nodes their judgments will be appropriately weighted.

Tip: A technique that can enhance the process of judging each member's influence within the group is to add a level above the players. This level might include factors such as experience, education, and political influence. Judgments would be made about the relative importance of these factors, and then about the relative degrees to which the players possess each factor.

The synthesis of the model from the goal will produce the overall priorities for the alternatives with respect to the goal. This process of evaluating the members can also be done in a separate model and the weights put into the original model.

Still another way to combine individual judgments is to make numbered copies of a model. Each individual makes judgments in his or her own copy of the model. The solution is obtained for each individual model. An arithmetic average is then taken of the solutions. This represents the group solution. In summary, Expert Choice offers several methods of representing the varied interests in group decisions.

EC provides a process to merge the intuition, experience and judgments of many people. A shared decision making process can expose leaders of an organization to a broader range of views and arguments than is typically filtered up to them. This is another way that Expert Choice serves as a useful vehicle for communication.

APPENDIX C

AHP METHODOLOGY

AHP METHODOLOGY

AHP can be characterized as a multi-criteria decision technique in which qualitative factors are of prime importance. A model of a simplified problem[1] (RPD prioritization) is developed using a hierarchical representation. At the top of the hierarchy is the overall goal or prime objective one is seeking to fulfill. The succeeding lower levels then represent the progressive decomposition of the problem. Knowledgeable parties complete a pair-wise comparison of all entries in each level relative to each of the entries in the next higher level of the hierarchy. The composition of these judgments fixes the relative priority of the entities at the lowest level (RPD alternatives) relative to achieving the top-most objective (System Goal 1 in the example).

The Analytic Hierarchy Process (AHP)

This technique is especially suited for application to problem evaluations in which qualitative factors dominate. It can be characterized as a multi-criteria decision technique that can combine qualitative and quantitative factors in the overall evaluation of alternatives. This section provides an introduction to AHP with an emphasis on the presentation of the general methodology. No attempt is made to provide the mathematical foundations for AHP; rather the interested reader is referred to [19] and [20].

AHP determines the priority any alternative has on the overall goal of the problem of interest. The analyst/user creates a model of the problem by developing a hierarchical decomposition representation. At the top of the hierarchy is the overall goal or prime objective one is seeking to fulfill. The succeeding lower levels then represent the progressive decomposition of the problem. The analyst, or other knowledgeable party, completes a pair-wise comparison of all elements in each level relative to each of the program elements in the next higher level of the hierarchy. The composition of these judgments fixes the relative priority of elements in the lowest level relative to achieving the top-most objective.

Four Steps are used to solve a problem with the AHP methodology:

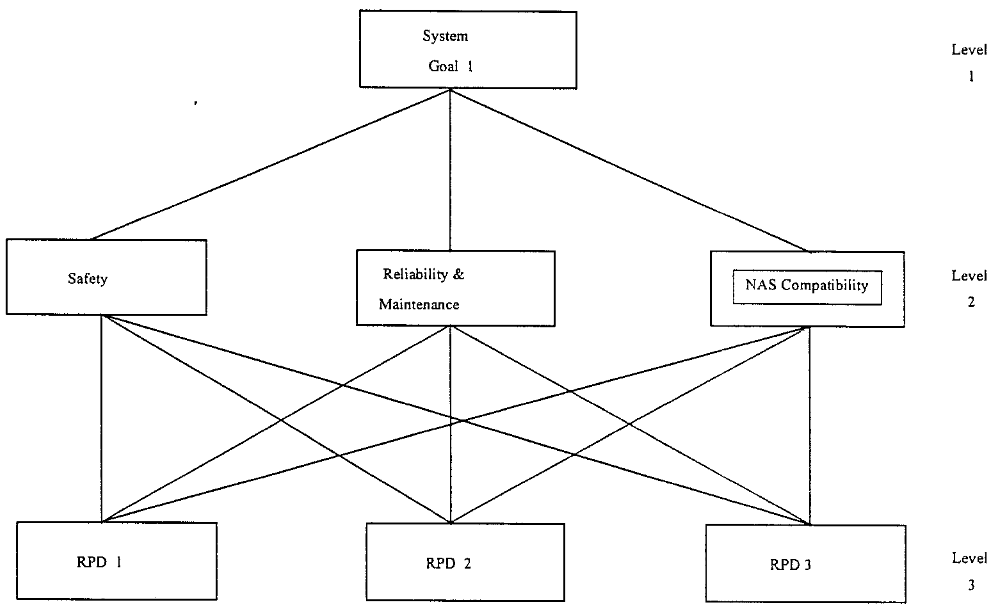
1. Build a decision "hierarchy" by breaking the general problem into individual criteria. (Modeling Phase)

2. Gather relational data for the decision criteria and alternatives and encode using the AHP relational scale [see following example]. (Pairwise Comparison)

3. Estimate the relative priorities (weights) of the decision criteria and alternatives (AHP software [3], [4] or a PC-spreadsheet [5]).

4. Perform a composition of priorities for the criteria, which gives the rank of the alternatives (usually lowest level of hierarchy) relative to the top-most objective (AHP software or a spreadsheet).

Many example applications of AHP can be found in the literature. See, for instance, [19], [20] and http://www.expertchoice.com. The AHP steps described above can be best understood through a discussion of an example application. Consider the example hierarchy presented below.



In this example the decision problem is to determine the priority rankings of three different RPD's that are under consideration for funding. The non-quantitative considerations (as displayed in the above figure) are safety, reliability/maintainability (R&M) and NAS compatibility. AHP will be utilized to determine the highest-ranking RPD based on these non-quantitative considerations. This determination will be based on the subjective judgment/experience of the decision maker(s). Stepwise details of the AHP methodology are presented below:

Step 1. Develop the hierarchical representation of the problem. At the top of the hierarchy is the overall objective and the decision alternatives are at the bottom. Between the top and bottom levels are the relevant attributes of the decision problem, such as selection criteria and the various "actors " (individuals, agencies and organizations), if appropriate, that provide significant input on the decision process. The number of levels in the hierarchy depends on the complexity of the problem and the analyst/decision maker's model of the problem hierarchy. In our example we have limited ourselves to just three levels since we are most interested in illustrating the workings of AHP (at present) rather than solving a specific priortization problem.

Step 2. Generate relational data for comparing the alternatives. This requires the analyst (decision-maker) to make pairwise comparisons of elements at each level relative to each activity at the next higher level in the hierarchy.

In AHP a relational scale of real numbers from 1 to 9 is used to systematically assign preferences. When comparing two attributes (or alternatives) A and B, with respect to an attribute U, in a higher level, the following numerical relational scale is used:

1 - A has the same importance as B with respect to U
3 - A has slightly more importance than B with respect to U.
5 - A has more importance than B with respect to U.
7 - A has a lot more importance than B with respect to U.
9 - A totally dominates B with respect to U.
1/3 - B has slightly more importance than A with respect to U.
1/5 - B has more importance than A with respect to U.
1/7 - B has a lot more importance than A with respect to U.
1/9 - B totally dominates A with respect to U.

Intermediate numbers are used for finer resolution.

In this example the importance of each criterion (level 2 entries) relative to system goal 1 (level 1 entry) needs to be established. Thus **focusing on system goal 1** we would provide comparisons (using the scale above) by answering the following questions:

1. Whats the relative importance of safety vs R&M with regard to system goal 1?
2. Whats the relative importance of safety vs NAS compatibillity with regard to system goal 1?
3. Whats the relative importance of R&M vs NAS compatibility with regard to system goal 1?

The answers to these questions, when translated to numerical equivalents, are presented below in the **Focus: System Goal 1** portion of numerical results.

Then we would compare each RPD (level 3) with respect to each criterion (level 2). This would be accomplished by again answering structured questions. For example when focusing on system safety:

1. Whats the relative importance of RPD 1 vs RPD 2 when focusing on system safety?
2. Whats the relative importance of RPD 1 vs RPD 3 when focusing on system safety?
3. Whats the relative importance of RPD 2 vs RPD 3 when focusing on system safety?

Then we would generate equivalent questions for a focus on R&M and then a third set of equivalent questions would be composed for a focus on NAS compatibility.

The answers to all these questions using the AHP numerical scale are tabulated in the results below organized by focus.

Step 3 Utilizing the pairwise comparisons of step 2 an eigenvalue method (mathematical approach used by AHP-see [1]) is used to determine the relative priority of each attribute to each attribute one level up in the hierarchy. In addition, a "consistency ratio" is calculated and displayed. According to Saaty [18], small consistency ratios (less than 0.1 is the suggested rule-of-thumb) do not drastically affect the ratings. The user has the option of redoing the comparison matrix if they wish to improve on the consistency ratio.

Step 4 In this step, the priorities (or weights) of the lowest level alternatives relative to the top most objective are determined and displayed.

Note to Potential User of AHP: *Fortunately, computations are made transparent by AHP software such as Expert Choice. Once the hierarchy is established, the software will systematically lead the decision maker through the necessary pairwise comparisons to establish the priorities and ratings. After each set of comparisons is completed, the software will provide information regarding the consistency of the judgments by reporting the inconsistency ratio and prompt the user to redo the judgments as appropriate. Once completed the software will compute the ratings (i.e. relative priorities of bottom alternatives upon the top most goal or objective).*

For the example system hierarchy (above) the AHP values are given in the following numerical results. We see from the ratings (or overall priorities for Focus: System Goal 1) that RPD 1 (rating of 0.399) and 2 (rating of 0.376) are approximately tied for best whereas RPD 3 (rating of 0.225) does not appear to be nearly as competitive.

Numerical Results

FOCUS: System Goal 1

Pairwise Comparison Matrix | Priorities | Ratio

$$\begin{bmatrix} 1 & 5 & 1 \\ 1/5 & 1 & 1/3 \\ 1 & 3 & 1 \end{bmatrix} \begin{matrix} 0.481 \\ 0.114 \\ 0.405 \end{matrix} \quad 0.025$$

FOCUS: Safety

Pairwise Comparison Matrix | Priorities | Ratio

$$\begin{bmatrix} 1 & 1/5 & 1/3 \\ 5 & 1 & 3 \\ 3 & 1/3 & 1 \end{bmatrix} \begin{matrix} 0.105 \\ 0.637 \\ 0.258 \end{matrix} \quad 0.033$$

FOCUS: Reliability & Maintenance

Pairwise Comparison Matrix | Priorities | Ratio

$$\begin{bmatrix} 1 & 2 & 1 \\ 1/2 & 1 & 1/3 \\ 1 & 3 & 1 \end{bmatrix} \begin{matrix} 0.387 \\ 0.169 \\ 0.444 \end{matrix} \quad 0.016$$

FOCUS: NAS Compat.

Pairwise Comparison Matrix | Priorities | Ratio

$$\begin{bmatrix} 1 & 6 & 6 \\ 1/6 & 1 & 1 \\ 1/6 & 1 & 1 \end{bmatrix} \begin{matrix} 0.75 \\ 0.125 \\ 0.125 \end{matrix} \quad 0.0$$

OVERALL PRIORITIES 0.399 0.376 0.225

We have already detailed what the overall ratings or priorities represent. Now we explain what the intermediate priorities, presented in conjunction with each FOCUS, in the numerical results represent.

FOCUS: System Goal 1
Priority 0.481 represents the relative importance of safety with regard to system goal 1
0.114 represents the relative importance of R&M with regard to system goal 1
0.405 represents the relative importance of NAS compatibility with regard to system goal 1

FOCUS: Safety
Priority 0.105 represents that relative importance of RPD 1 with regard to safety
0.637 represents that relative importance of RPD 2 with regard to safety
0.258 represents that relative importance of RPD 3 with regard to safety

FOCUS: Reliability & Maintenance (R&M)
Priority 0.387 represents that relative importance of RPD 1 with regard to R&M
0.169 represents that relative importance of RPD 2 with regard to R&M
0.444 represents that relative importance of RPD 3 with regard to R&M

FOCUS: NAS Compatibility
Priority 0.75 represents that relative importance of RPD 1 with regard to NAS compat.
0.125 represents that relative importance of RPD 2 with regard to NAS compat.
0.125 represents that relative importance of RPD 3 with regard to NAS compat.

Concluding Remarks

AHP facilitates a comprehensive and logical analysis of problems for which considerable uncertainty exists. If fact, the power of AHP (and to a large degree its uniqueness) is being able to consider qualitative goals and attributes within its framework. The method of pairwise comparisons is systematic and comprehensive. One might want to repeat a set of pairwise comparisons if the consistency ratio is alarmingly high. The final output from the AHP software is the relative priorities of the bottom most (in the hierarchy) alternatives relative to the overall objective (top level of hierarchy). Intermediate priorities may also be provided upon demand.

AHP has been reported as being effective in hundred of different applications (see [17] and Appendix A). In particular AHP has become known as an effective modeling and analysis tool because:

- It handles qualitative considerations in a logical and consistent manner.
- It has been shown to be valid from a mathematical and scientific view point.
- It capable of handling uncertainty in a natural and consistent manner.
- It is applicable to the largest and most complex problems faced by analysts.
- It can easily incorporate scenario-based frameworks.
- It can facilitate group decision making.
- It can handle dependencies between alternatives (these were the RPD's in our example)
- It can consider the dynamic situation of time dependency.
- User friendly PC-based software is available to perform the required AHP calculations.
- AHP software provides the user with a measure of how consistent each set of comparisons turned out to be.
- AHP software is capable of easily generating volumes of sentivity analyses.

According to [20] there are many reasons that people find AHP easy to use. Namely,

- People find it natural and are usually attracted rather than alienated by it.
- It does not need advanced technical knowledge and nearly everyone can use it. According to Saaty "it takes about an hour to introduce it to my students with Expert

Choice and they go on to do substantial examples."

- It takes into consideration judgments based on people's feelings and emotions as well as their thoughts.

- It deals with intangibles side by side with tangibles. What we perceive with the senses is dealt with by the mind in a similar way to what we feel.

- It derives scales through reciprocal comparison rather than by assigning numbers pulled from the mind directly.

- It does not take for granted the measurements on scales, but asks that scale values be interpreted according to the objectives of the problem.

- It relies on simple to elaborate hierarchic structures to represent decision problems. With such appropriate representation, it is able to handle problems of risk, conflict and prediction.

- It can be used to make direct resource allocation, benefit/cost analysis, resolve conflicts, design and optimize systems.

- It is an approach that describes how good decisions are made rather than prescribes how they should be made. No one living at a certain time knows what is good for people for all time.

- It provides a simple and effective procedure to arrive at an answer, even in group decision making where diverse expertise and preferences must be considered.

- It can be applied in negotiating conflicts by focusing on relations between relative benefits to costs for each of the parties. (see Chapter 7 of [6])

Finally, the open literature details many successful applications in industry and government of AHP. See Appendix A and [17] for a listing of these applications.

APPENDIX D

SUMMARY OF ACCOMPLISHMENTS

SUMMARY OF ACCOMPLISHMENTS

FAA Grant – Planning Allocations to Research & Development Projects

FAA PROJECT MANAGER: Dave Nesterok

TITLE: Planning FAA's Resource Allocations to Research and Development Projects

RESEARCHERS: Les Frair, Robert Batson, Amit Deshpande, DeBarion Taylor

ACCOMPLISHMENTS:

1. Interactions with FAA Airport and Aircraft Safety Personnel
2. Interactions with FAA Human Factors Personnel
3. Training of UA Researchers on Utilization of NASDAC Databases
4. Interactions with Dept. of Navy Personnel on R&D Allocation Methodologies
5. Interactions with Dept. of Air Force Personnel on R&D Allocation Methodologies
6. Interactions with NASA Personnel on R&D Allocation Methodologies
7. Interactions with DOD Contractor Personnel on R&D Allocation Methodologies
8. Completion and Documentation of Literature Search concerning R&D Allocation Methodologies
9. Completed and Documented Detailed Evaluation of R&D Allocation Methodologies
10. Selected Multicriteria Decision Making Methodology as Recommended FAA Tool
11. Documented Detailed Discussion of Recommended FAA Tool (The Analytic Hierarchy Process (AHP))
12. Developed and Presented Several AHP Models of R&D Allocation Problem to FAA Personnel
13. Documented and Presented Description of AHP Solution Procedure to FAA Personnel
14. Documented and Presented Comparison of AHP with Other Candidate Methodologies
15. Formal Presentation of Research Results to FAA Personnel on July 29, Aug. 18, Oct. 22 and Nov. 9, 1998
16. Interacted with Expert Choice Software Company Concerning AHP Software Demonstration for Selected FAA Personnel

APPENDIX E

PLANNING FAA'S RESOURCE ALLOCATION TO RESEARCH AND DEVELOPMENT PROJECTS – A RECOMMENDED APPROACH

Internet Approach -

1. Interaction via the internet to develop an AHP model for R&D investment problem of interest

2. Once a consensus model has been developed (1. above) develop an interactive internet program to gather FAA evaluations

3. Present the results of steps 1 & 2 (above) via the internet for discussion and evaluation

4. Present the results of step 3

A Possible Interaction - Provide Proof of Concept

- **Interaction with a selected FAA group to model and analyze investment R&D problem(s) using AHP**

- **Several stage process interaction between FAA and UA researchers (Frair, Batson, & Deshpande)**

Possible Stages

1. **UA interact with selected FAA group to develop an AHP R&D investment model for consideration**

2. **UA collaborate with selected FAA group to obtain AHP modeling consensus and solicit evaluation input.**

3. **UA produce analysis results for step 2 above and provide to FAA selected group or subgroup for evaluation and feedback**

4. **UA presentation(s) documenting this process, results achieved, and FAA evaluation feedback**

AHP - Model Building

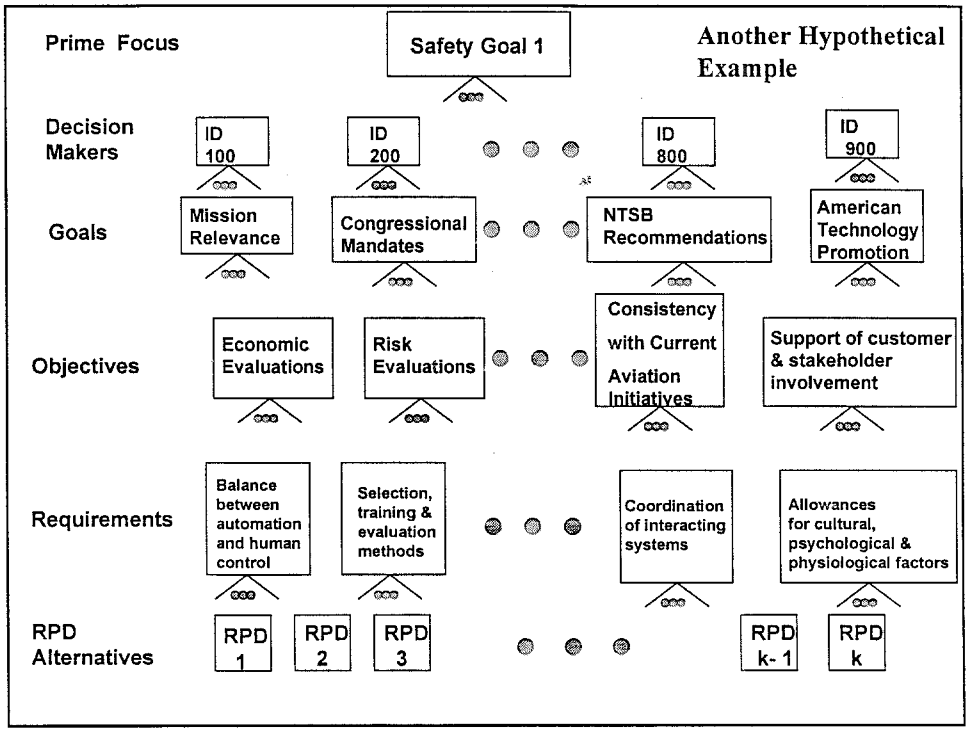
Advanced Considerations

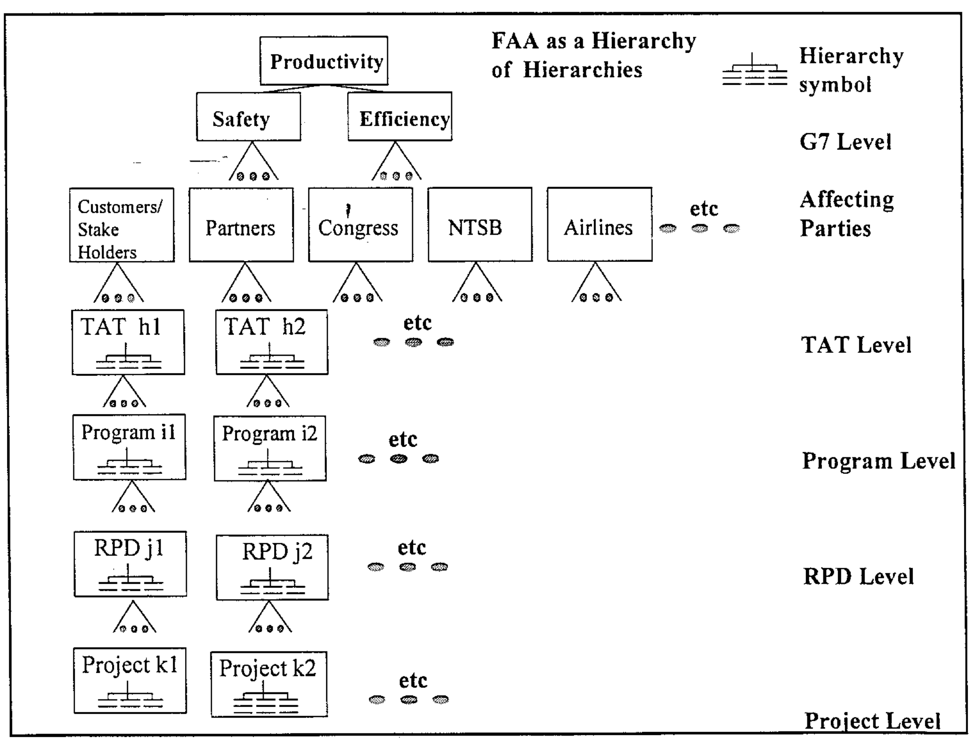
- Dependencies between entities
- Time frame considerations
- Linking AHP's together

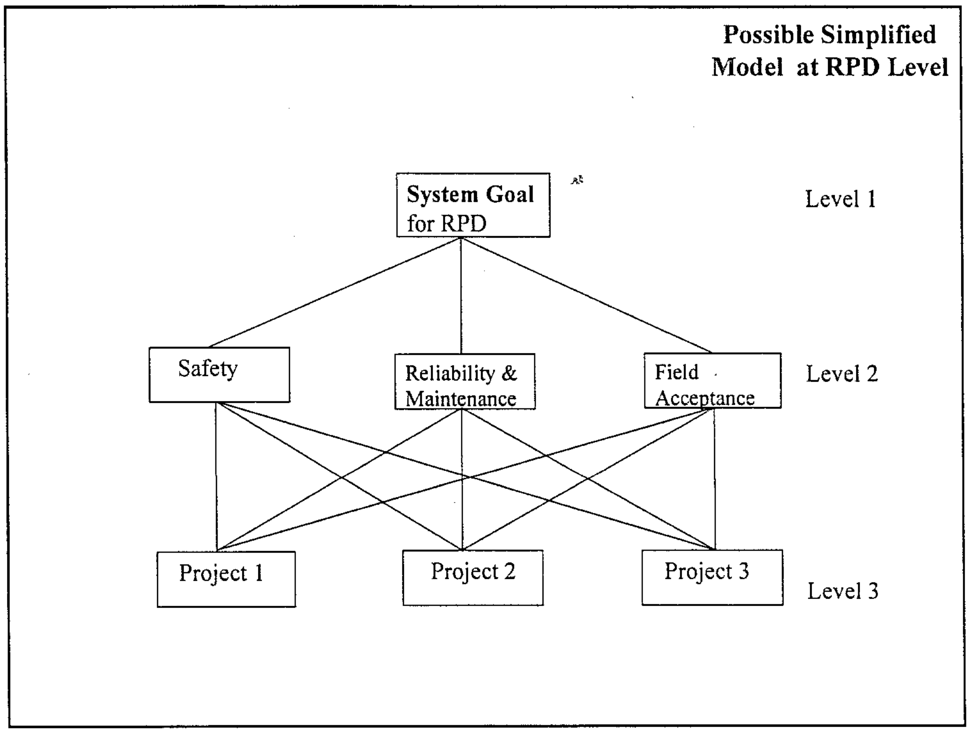
How could such models be built and analyzed?

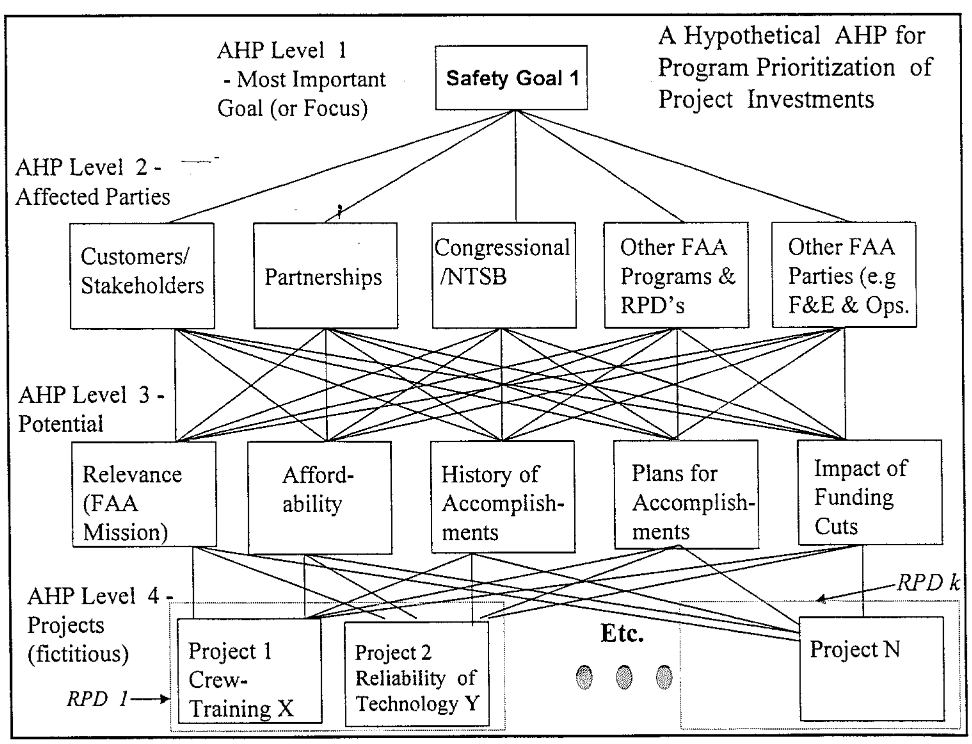
Possible Approaches:

- Concentrated development project for FAA decision makers with AHP facilitators
- Facilitators act as liaisons with the responsible FAA parties - internal periodic effort
- Interactive Web-Based Approach


Prime Focus
Safety Goal 1
Another Hypothetical Example
Decision Makers
ID 100
ID 200
ID 800
ID 900
Goals
Mission Relevance
Congressional Mandates
NTSB Recommendations
American Technology Promotion
Objectives
Economic Evaluations
Risk Evaluations
Consistency with Current Aviation Initiatives
Support of customer & stakeholder involvement
Requirements
Balance between automation and human control
Selection, training & evaluation methods
Coordination of interacting systems
Allowances for cultural, psychological & physiological factors
RPD Alternatives
RPD 1
RPD 2
RPD 3
RPD k- 1
RPD k


Productivity
FAA as a Hierarchy of Hierarchies
Hierarchy symbol
Safety
Efficiency
G7 Level
Customers/ Stake Holders
Partners
Congress
NTSB
Airlines
etc
Affecting Parties
TAT h1
TAT h2
etc
TAT Level
Program i1
Program i2
etc
Program Level
RPD j1
RPD j2
etc
RPD Level
Project k1
Project k2
etc
Project Level


Possible Simplified Model at RPD Level
System Goal for RPD
Level 1
Safety
Reliability & Maintenance
Field Acceptance
Level 2
Project 1
Project 2
Project 3
Level 3


AHP Level 1 - Most Important Goal (or Focus)
Safety Goal 1
A Hypothetical AHP for Program Prioritization of Project Investments
AHP Level 2 - Affected Parties
Customers/ Stakeholders
Partnerships
Congressional /NTSB
Other FAA Programs & RPD's
Other FAA Parties (e.g F&E & Ops.
AHP Level 3 - Potential
Relevance (FAA Mission)
Afford- ability
History of Accomplish- ments
Plans for Accomplish- ments
Impact of Funding Cuts
RPD k
AHP Level 4 - Projects (fictitious)
Project 1 Crew- Training X
Project 2 Reliability of Technology Y
Etc.
Project N
RPD 1

Pairwise Comparisons of Alternatives

Focus

Congestion	**A vs B; A vs C; B vs C**
Weight	**A vs B; A vs C; B vs C**
Cost:	**A vs B; A vs C; B vs C**
Renovation	**Congestion vs Weight; Congestion vs Cost; Weight vs Cost**

Using a relational scale of real numbers from 1 to 9 to systematically assign preferences. When comparing two attributes (or alternatives) X and Y, with respect to an attribute U, in a higher level, the following numerical relational scale is used:

Coding

- 1 - X has the same importance as Y with respect to U
- 3 - X has slightly more importance than Y with respect to U.
- 5 - X has more importance than Y with respect to U.
- 7 - X has a lot more importance than Y with respect to U.
- 9 - X totally dominates Y with respect to U.
- 1/3 - Y has slightly more importance than X with respect to U.
- 1/5 - Y has more importance than X with respect to U.
- 1/7 - Y has a lot more importance than X with respect to U.
- 1/9 - Y totally dominates X with respect to U.

Intermediate numbers are used for finer resolution.

Note: Software does not require user to define numbers but just to specify the appropriate relationship

AHP - Possible Use by FAA

AHP could be used at any level of the organization to prioritize (or rank) investments in RD&E

- Could be accomplished by group

- Could be accomplished by individual or individuals

For Example -

- RPD Level
- Program Level
- Higher Level (e.g. TAT or G7)

Relational data from pairwise comparisons of taxiway criteria

Coding

1 - X has the same importance as Y with respect to U
3 - X has slightly more importance than Y with respect to U.
5 - X has more importance than Y with respect to U.
7 - X has a lot more importance than Y with respect to U.
9 - X totally dominates Y with respect to U.
1/3 - Y has slightly more importance than X with respect to U.
1/5 - Y has more importance than X with respect to U.
1/7 - Y has a lot more importance than X with respect to U.
1/9 - Y totally dominates X with respect to U.
Intermediate numbers are used for finer resolution.

	Criterion U= Taxiway Renovation	Y= Congestion	Y= Weight	Y= Cost
X=	Congestion	1	1/2	1/ 5
	Weight	2	1	1/3
	Cost	5	3	1

The Taxiway Example

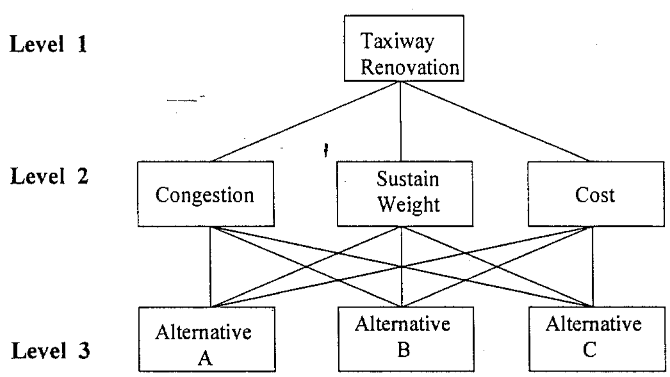
Relational Data - Pairwise Comparisons of Alternatives

Criterion	Alternative A	Alternative B	Alternative C
Congestion			
Alternative A	1	6	4
Alternative B	1/6	1	2/3
Alternative C	1/4	3/2	1
Weight			
Alternative A	1	1/3	1/5
Alternative B	3	1	1/2
Alternative C	5	2	1
Cost	$5M	$4M	$3M
		Ratings	
Criteria			
Congestion (0.122)	0.706*	0.118	0.177
Weight (0.230)	0.109	0.309	0.582*
Cost (0.648)	0.255	0.319	0.426*
Overall	**0.276**	**0.291**	**0.433***

We will first attempt to illustrate how AHP works with a very simple example.

We have made use of data from an Air Force economic analysis.

The decision problem was the repair or replacement of an aircraft taxiway.



Alternative A: Repair the old taxiway

Alternative B: Construct new taxiway with material recycled from old taxiway

Alternative C: Construct new taxiway and dispose of materials from old taxiway

In Addition - AHP

- Software readily available
- Built-in measure of consistency of judgments
- Sensitivity analyses easily conducted
- Group decisions facilitated by
  - Combination of individual evaluations
  - Collaborative evaluations

AHP Overview

Origin: Thomas Saaty- 1970's

Multi-criteria decision making technique in which qualitative factors are very important

- Problem of interest is represented (or modeled) in a hierarchy of considerations
- At top of the hierarchy is the top-most objective (or prime focus)
- Succeeding lower levels represent the progressive consideration of the problem from the top-most objective down to the lowest level usually corresponding to the alternatives under consideration
- Complete pair-wise comparisons of all entries in each level relative to each of the entries in the next higher level are accomplished
- Composition of these comparisons determines the relative priority of the entries at the lowest level relative to the top-most objective

In our final report we provide 11 reasons why **AHP** has gained the reputation as an **effective modeling** and **analysis methodology**

For Example

- It handles qualitative considerations in a logical and consistent manner
- It is capable of handling uncertainty and time dependency in a natural and consistent manner
- PC-based user friendly software available to perform the desired AHP calculations
- For mission-oriented organizations, it can be used to establish linkages between lower level operations and requirements with upper level mission areas, strategies, etc.

In our final report we also provide 11 reasons why **AHP** has gained the reputation as being **easy to use.**

For Example

- It deals with intangibles side by side with tangibles
- It provides a simple and effective procedure to arrive at an answer, even with group decision making where diverse expertise and preferences must be considered
- It can take into account judgments based on people's feelings and emotions as well as logical conclusions
- Users find it natural and are usually attracted rather than repulsed by it.

Evaluation of Decision Making Methods

Srisoepardani in his dissertation compared 16 different Decision Making methods with respect to 12 evaluation parameters

RESULTS

The AHP technique was rated highest for every evaluation parameter except one. That is it had the highest evaluation for 11 parameters and was second highest for one parameter.

Decision Making Methodologies

We have reviewed over 20 candidate methods for making decisions concerning investment in R&D opportunities.

We have identified the strengths, weaknesses, scope and reported applications of these techniques. In addition we have estimated the adaptability and robustness of the leading candidates for determining FAA allocations to R&D activities under consideration .

Our conclusion is that the **Analytic Hierarchy Process (AHP)** is **superior** to the other techniques considered for R&D investment analyses.

Planning FAA's Resource Allocations to Research and Development Projects

Discussion & Briefing - FAA Technical Center

Atlantic City, NJ. - November 9, 1998

Les Frair
Robert Batson (Co-PI)
Amit Desphande (GRA)

FAA Project Manager: Dave Nesterok

FAA R & D Investment Problem

Determine the priorities for investment in any set of R&D alternatives.

Approach

Investigate methodologies that have the capability to consider qualitative and quantitative factors for setting R&D investment priorities.

Results

Recommend the use of the "Analytic Hierarchy Process" (AHP)